INTEGRATING UAS FLOCKING OPERATIONS WITH FORMATION DRAG REDUCTION

THESIS

Jacob L. Lambach, Captain, USAF

AFIT-ENV-14-M-01DL

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Captain, USAF

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Abstract

Craig Reynolds, in the seminal research into simulated flocking, developed a methodology to guide a flock of birds using three rules: collision avoidance, flock centering, and velocity matching. By modifying these rules, a methodology was created so that each aircraft in a "flock" maintains a precise position relative to the preceding aircraft. By doing so, each aircraft experiences a decrease in induced aerodynamic drag and increase in fuel efficiency. Flocks of semi-autonomous aircraft present the warfighter with a wide array of capabilities for accomplishing missions more effectively. By introducing formation drag reduction, overall fuel consumption is reduced while range and endurance increase, expanding war planners' options. A simulation was constructed to determine the feasibility of the drag reduction flock in a two-dimensional environment using a drag benefit map constructed from existing research. Due to both agent interaction and wind gust variability, the optimal position for drag reduction presented a severe collision hazard, and drag savings were much more sensitive to lateral (wingtip) position than longitudinal (streamwise) position. By increasing longitudinal spacing, the collision hazard was greatly reduced and a 10-aircraft flock demonstrated a 9.7% reduction in total drag and 14.5% increase in endurance over a mock target.

To my wife, whom I met while selecting my thesis topic, started dating as I finished Chapter I, proposed to at the end of Chapter III, and wed right after thesis defense. Your support and patience through the whole process was crucial.

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Jacob L. Lambach

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INTEGRATING UAS FLOCKING OPERATIONS WITH FORMATION DRAG REDUCTION

I. Introduction

General Issue

The recent operations by the United States Department of Defense in Iraq, Afghanistan, and other countries of the Middle East have demonstrated the growing importance of the Unmanned Aircraft System (UAS). As the UAS grows in prominence, the Department of Defense (DOD) continually searches for new roles and opportunities for its use. The DOD is seeking to revolutionize the uses of airpower by taking advantage of unique UAS capabilities such as increased loiter time, portability, and survivability. The United States Air Forces Unmanned Aircraft Systems Flight Plan 2009-2047 describes a vision to direct research and development for how they potentially will be used in the future.

One capability mentioned in this Flight Plan is the ability "to swarm (one pilot directing the actions of many multi-mission aircraft) creating a focused, relentless, and scaled attack." Very similar to swarming, flocking offers many new capabilities to the war fighter. Increased payload, more eyes in the sky and lower pilot workload are among the most obvious benefits, though new advantages will undoubtedly be revealed as the technology is implemented. Additionally, the capability to accomplish the same mission as current conventional platforms by substituting a fuel efficient flock will be advantageous in an era of diminishing defense budgets, especially because smaller scale UASs are currently an order of magnitude cheaper than conventional platforms. Finally, a flock will be beneficial for civilian reconnaissance missions such as search and rescue or environmental measurements.

Like many technological advances, the flocking concept originates from the animal kingdom. Birds (most notably geese), fish, and many types of insects employ flocking or swarming for a variety of reasons, including: mutual protection, shared navigational responsibility, and increased efficiency. Manned military aircraft already utilize formation flying for many of these same reasons. Competitive cyclists also employ a form of flocking to conserve energy during races, although the aerodynamic causes for this phenomenon are different: cyclists experience a reduction in parasite drag rather than induced drag. The "value added" for flocking of aircraft is that a single operator can control and direct the efforts of the entire flock while the flock itself manages issues such as intra-flock collision prevention (known as de-confliction) and terrain avoidance.

Significant research into the flocking concept has already been undertaken in the paramount issues of collision avoidance and task allocation. However, one major benefit of the flocking concept in the biological world that has not been fully integrated into this research is the increased efficiency of flocking. If the geese fly in an appropriate formation, each goose takes advantage of the updraft created by the wings of the others, experiencing an efficiency bonus and decreased workload. While significant research has also been done into the increased efficiency gained by taking advantage of wake vortices from previous aircraft, it has not been integrated with autonomous flocks of more than three aircraft.

Problem Statement

There are many benefits to creating a flock of semi-autonomous Unmanned Aircraft Systems to provide increased persistence, payload, and visibility over a battle space. However, most current solutions feature a somewhat haphazard grouping of aircraft that work together toward a common goal: either moving through a defined set of waypoints or providing persistent coverage over an area of interest. The flock of UASs is able to maintain collision avoidance while each flock member also quasi-independently determines its own course. However, a much more precise form of station keeping is required in order to reap the benefits of induced drag reduction associated with formation flight. Studies assert that utilizing wake vortices can reduce induced drag by up to 54%, resulting in greatly decreased fuel consumption and increased range and endurance (Kless, et al. 2012, 11). There is also significant existing research exploring the proper positioning of trailing aircraft in order to take advantage of these updrafts created by wake vertices. However, the proximity and coordination required to yield significant drag reduction benefits are significantly more complex than that of existing flocking models. As such, flocking models and formation drag reduction research are, up to this point, mutually exclusive. This thesis integrates emerging flocking research with emerging formation drag reduction research to take advantage of the benefits of both and provide new capabilities to the UAS fleet.

Research Objectives/Questions/Hypotheses

This thesis seeks to determine whether flocking aircraft can utilize formation flying to experience a reduction in induced drag. The following questions will be addressed:

- How does the formation affect aerodynamic properties such as optimum cruise speed?
- What formation position provides the optimum combination of drag reduction and collision avoidance?
- What descriptive parameters and procedures of the flock/formation drive increased utility, such as increased range and ability to accomplish a variety of mission sets?
- What control mechanism provides the optimum compromise between collision avoidance and station-keeping?

The hypothesis is that a control mechanism can be developed that will allow a flock of UASs to fly in a goose-like "V" formation during certain phases of flight to increase fuel efficiency, range, and endurance.

Research Focus

The focal point of the research is a simulation constructed using MATLAB. It has been extensively modified from a similar flocking simulation developed by Dr. John Colombi, Professor of Systems Engineering at the Air Force Institute of Technology. In the new simulation, a flock is constructed that navigates through a set of waypoints while attempting to maintain the appropriate formation position so that each aircraft may benefit from the preceding aircraft's wake vortices. It uses aerodynamic benefit maps developed in other research and determines the fraction of time each individual aircraft is able to reap these benefits. These observations allow the ultimate effects on fuel consumption, range, and endurance to be calculated empirically. Different variations of the control methodology were tested to determine which was most effective in increasing flock range and endurance.

Methodology

The research took place using simulations of flocking aircraft in a two-dimensional plane. Existing research into wake vortex distributions was used to determine positions where reductions in induced drag could be expected. First, tests were conducted to determine appropriate control logic to efficiently position the flock in the proper formation. After this was accomplished, the flock executed a mock mission and Measures of Performance were assessed. Additionally, each formation was allowed to fly to its maximum range to study how formation procedures and cruise speeds affect range and endurance.

Assumptions/Limitations

The simulation is constructed in a two-dimensional environment, while aircraft obviously operate with a third dimension. Although the vertical dimension does affect optimal positioning, the rate at which the wake vortices descend is fairly well-documented. It is assumed that a control methodology which effectively manages a flock in two dimensions will be able to handle a third dimension satisfactorily, especially because maneuvering in the vertical dimension is minimal. In fact, rather than increasing complexity, the addition of the third dimension is hypothesized to greatly simplify collision avoidance. The aircraft could be separated vertically, allowing horizontal freedom of movement and greatly simplifying the process of maneuvering to the proper horizontal position. After reaching a stable horizontal position, the aircraft could than initiate a slight climb or descent into the desired position.

The simulation also assumes that all aircraft in the flock are accurately aware of the position of all other aircraft in the formation at all times. Technology already exists to exchange this information, such as TCAS and Link-16, but whether the accuracy and update frequency of current technology is sufficient for formation drag reduction is doubtful. Instrumentation systems have demonstrated the ability to exchange relative position information with 10 cm accuracy for a formation of 2 aircraft, but more sophisticated technology would be required to extend this to a larger flock (Larson and Schkolnik 2004, 8). Additionally, the simulation assumes that each aircraft is able to collect information on the position of the rest of the flock, calculate a desired steering command, and execute that command at a frequency of once per second. This frequency was generally sufficient for the simulation, and performance improved when a higher frequency was used. Finally, although random wind gusts and turbulence are incorporated in the simulation, experience suggests that air disturbances not caused by the formation will generally affect the entire formation equally. As such, a random wind gust is computed for the entire simulation every time step rather than for each aircraft. Another step that could be implemented to increase realism of results would be to incorporate the Dryden wind turbulence model (United States Air Force 2004, 678-679).

Implications

The integration of flocking with formation drag reduction will allow war fighters to apply the UAS to increasingly complex missions. A flocking group of UASs will be able to increase range from their base and fly farther into enemy territory because of reduced drag. A formation maintaining an orbit over a designated target will be able to maintain persistent aerial coverage for a longer period of time if other considerations such as resolution and coverage area do not impact the ability to utilize formation drag reduction. Additionally, the reduction in induced drag will decrease the formation's endurance airspeed, enabling the formation to fly in a tighter circle over a designated target, thereby maintaining a closer proximity to that target.

The flock can increase payload by eliminating redundant components. For example, in a flock of 10 aircraft, a beyond-line-of-sight (BLOS) communications link could be removed from all aircraft in the formation except two or three, freeing up space for a larger payload of sensors or weapons while preserving redundancy. In this scenario a strike package could include many small aircraft instead of a small number of large ones, which could be advantageous because the smaller aircraft have much lower observability and higher survivability. This could additionally be advantageous for a high-risk mission where loss of some of the cheap, small aircraft is preferable to loss of the more expensive larger system.

The unique advantages of emerging systems are frequently not discovered until after a system is fielded for one purpose and then adapted to serve another. The apparent advantages of integrating flocking with formation drag reduction are significant and further out-of-the-box capabilities will certainly be discovered with time and creativity.

II. Literature Review

Chapter Overview

This thesis integrates research from a variety of vastly different fields, including aerodynamics, computer science, artificial intelligence, biology, animation, and military tactics. As a systems engineering thesis, it will not seek to increase the depth of knowledge in any of these fields but rather to connect and integrate them. This chapter will start by examining a sampling of various formation types currently used in military flying operations. Next it will explore a revolutionary new formation type adapted from biology that uses artificial intelligence to semi-autonomously maintain a loose grouping of aircraft oriented toward a common goal. Third, it will explore a precise formation position that takes advantage of updrafts produced by other aircraft to increase overall formation fuel efficiency. Finally, various techniques used to accurately maintain a desired position relative to a moving target will be explored. Overall, these loosely connected fields of study will be combined to give a broad picture of the state of technology. Enough depth is provided to give a general understanding of each of the various fields being integrated without becoming completely immersed into any of the various subjects.

Air Force Formation Procedures

The United States Air Force (USAF) utilizes formation flying for a multitude of purposes. In airlift/transport aircraft, formations are used to move a large number of aircraft with maximum efficiency or to airdrop a large amount of cargo in a short amount of time. In tanker aircraft, formations are used to provide more available fuel for receiver aircraft (or formations of receiver aircraft) with large fuel onload requirements. These formations can get quite large, as it is not uncommon for multiple formations of fighters to join with a tanker formation to create a mixed formation of 10+ aircraft. While formations are the exception in heavy military aircraft, in fighter aircraft operations it is rare to fly without a wingman. Formations provide mutual support for both tactical and non-tactical situations. Tactically, a two-ship or four-ship formation of fighters is able to control a battle space exponentially more effectively than a single fighter by using teamwork and wingman procedures. In non-tactical situations, the formation members provide mutual support in terms of navigation, communication, system malfunctions, and decision-making. A variety of formation positions are used for various situations and phases of flight but ultimately each formation has a purpose and is uniquely suited to the requirements of the mission.

As seen in Figure 1, fighter aircraft use a large number of formations and transition between them frequently in various phases of flight. Fingertip formation is primarily used for takeoffs, landings, and weather penetration. The extreme proximity enables the formation to maintain visual contact amidst all but the thickest of clouds. It is also used when it is necessary to communicate via hand signals such as in the case of radio equipment failure. However, maintaining this position requires the undivided attention of the wingman and is very fatiguing. Route position enables the formation to stay relatively close together while increasing the ability to maneuver, look out visually, or complete cockpit tasks such as checklists. The Fighting Wing position is rarely used, but enables to formation to maneuver rapidly when unexpected changes to the flight path are necessary (United States Air Force 2011, 71-80).

In addition to the aforementioned basic formation positions, fighter aircraft also use a category of formation positions referred to as Tactical Formation for weapons employment. In tactical formations, the aircraft are spaced approximately one mile apart to facilitate use of radar and weapons, as well as being able to “watch six” – watch for enemies sneaking up behind. The basic tactical formation is known as Tactical Line Abreast and features many variations as the formation increases to more than two aircraft. Another common variant of the tactical position is Wedge, which is primarily used in the low altitude environment because of increased maneuverability requirements (United States Air Force 2011, 86-98).

USAF Mobility (Heavy) aircraft also utilize formations frequently. As a rule, these aircraft are much larger and less maneuverable so the spacing between aircraft in the formation is considerably larger. As seen in Figure 2, the heavy aircraft are typically separated by approximately one mile. The Trail formation is primarily used for efficiently transporting a large group of aircraft a fairly large distance. When a formation of tanker aircraft are about to commence Air to Air Refueling (AAR), they typically transition from the Trail formation to the Echelon formation which provides a greater safety margin for AAR contingencies. Some heavy aircraft such as the C-17 have special Station Keeping Equipment (SKE) which enables them to maintain a specified formation position with respect to other aircraft in the formation. This equipment allows the aircraft to fly closer to each other for longer periods of time than they normally would without excessive pilot fatigue. This is especially helpful in completing large airdrops in a short period of time. When fighter aircraft join with a tanker for AAR, they typically join to the left wing (Observation), cycle back to the Contact position to accomplish the refueling, and then move to the right wing (Reform) to wait for their wingmen to complete AAR and then depart the formation to continue their mission (North Atlantic Treaty Organization 2010).

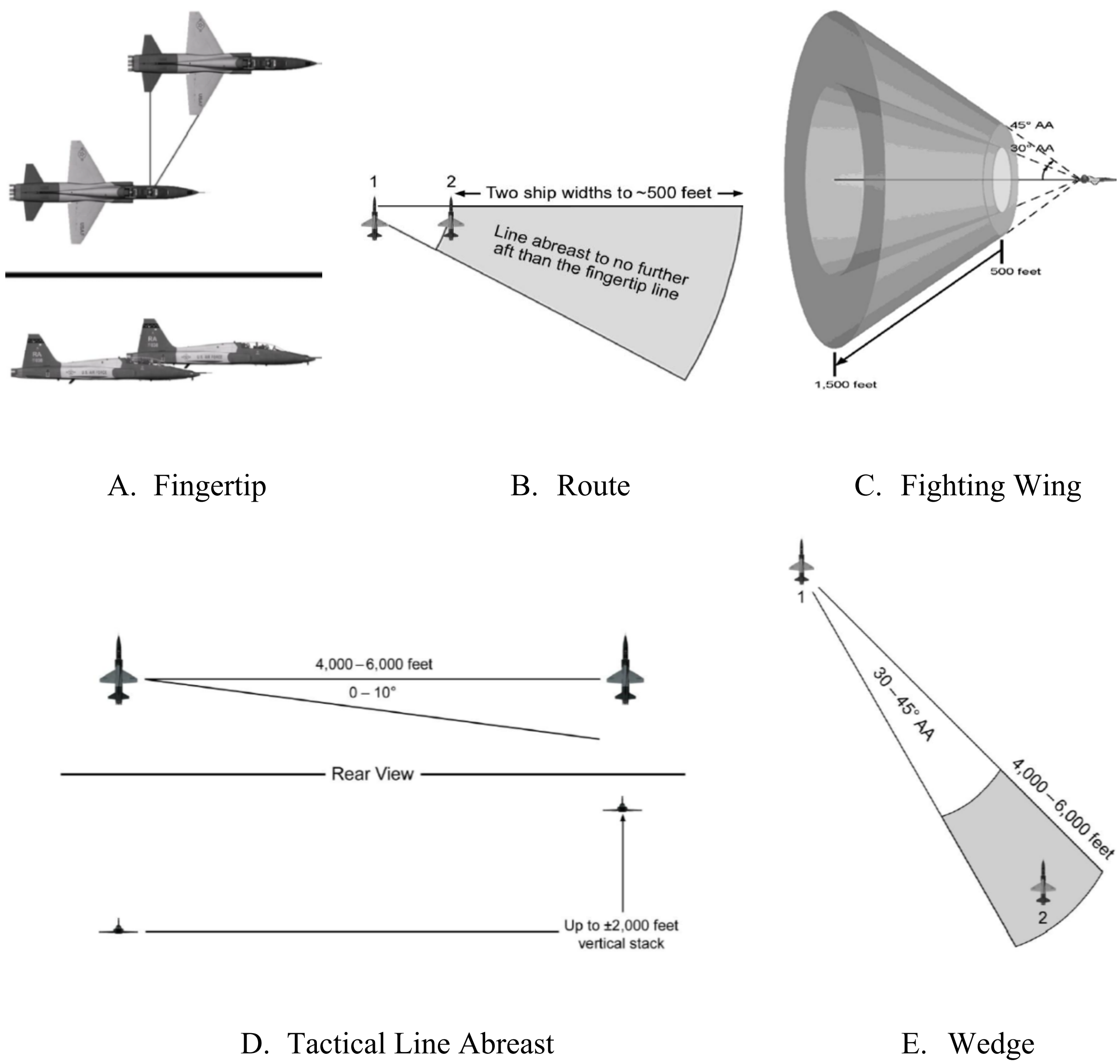
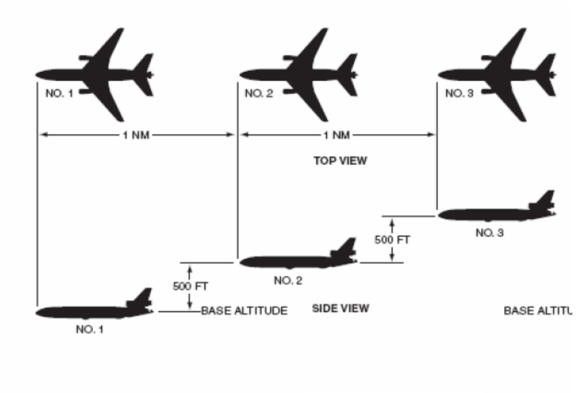
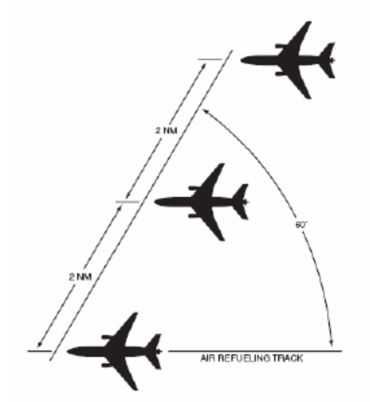


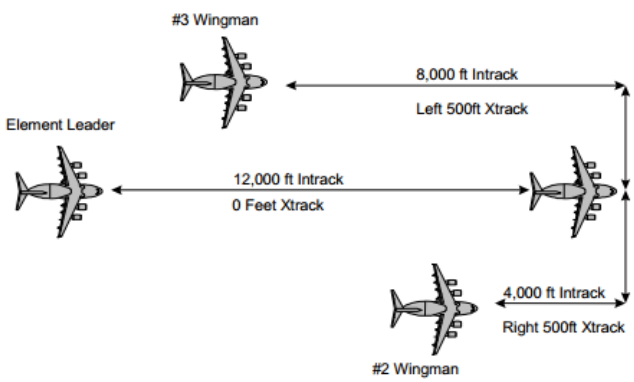
Figure 1: Typical Fighter Aircraft Formations (United States Air Force 2011, 71-72, 80, 87, 99)



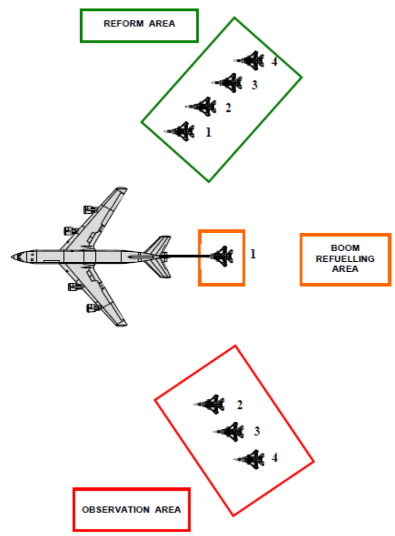
A. Trail



B. Echelon



C. SKE Formation



D. Observation/Contact/Reform

Figure 2: Typical Heavy Aircraft Formations (North Atlantic Treaty Organization 2010, 64,127-128), (United States Air Force 2011, 202)

While this list is not exhaustive, it provides a brief overview of the variety of formations and their ability to enhance mission effectiveness. These formations, accompanied by various tactics, techniques, and procedures (TTPs), serve as a force multiplier for USAF flying operations. Although this variety of formation positions is derived from decades of experience, the new capabilities of UASs provoke new ideas that were previously considered impossible. For example, the tendency of birds to form autonomous flocks was previously regarded as too complex for aircraft, but now the benefits of flocking can be leveraged using emergent technologies.

Flocking Research

The motivation for the flocking behavior displayed by many species of birds is a source of debate in the biological community. Many point to aerodynamic benefits of flying in a formation, which will be discussed extensively later in this thesis. However, this explanation is lacking because some species employ a loose cluster formation rather than the "V" formation, which maximizes aerodynamic benefit. Other theories include mutual defense against predators, ease of communication, and social behaviors, which are similar to the motivations listed above for Air Force fighter aircraft (Bajec and Heppner 2009, 779), (Nathan and Barbosa 2008, 180). Research suggests that the prior theory (aerodynamics) is more applicable to larger birds while the latter theories are more applicable for relatively smaller birds (Seiler, Pant and Hedrick 2002, 119).

The creative military planner will certainly be able to imagine many new capabilities that could be provided by a flock of UASs, especially if they are controlled by a single operator. For example, when performing a search (or rescue) operation a single search vehicle would have to make many passes over a designated grid to cover the entire area with its limited view swath. A flock of search aircraft will be able to cover the ground much more quickly and effectively, especially if the target is actively trying to elude detection by moving in anticipation of the search aircraft's passes (Labonté 2009, 4). Flocks of aircraft that are smaller than those currently being used will also have a reduced visual and acoustic signature to prevent detection by ground forces. By distributing the capabilities of one large aircraft into a flock of smaller aircraft, the radar signature is also reduced and could potential be confused with a flock of actual birds. When conducting a bombing mission, a flock of bomber aircraft will be able to ingress as a group, split up to bomb multiple targets simultaneously, and regroup to egress together, enabling a multiplicatively larger bombing force while maintaining the element of surprise. A mixed flock of reconnaissance, tanker, bomber, and air superiority UASs could be a self-sufficient combat unit capable of responding to a variety of contingencies. In addition, using solely UASs increases the overall reach of air power because remaining within range of search and recovery personnel is unnecessary without pilots on board (Innocenti, Giulietti and Pollini 2002, 2).

In order to implement a semi-autonomous flock of aircraft, most software architectures employ a variety of “rules” which are weighted variously in order to attain the desired flock cohesion. Craig Reynolds originated this concept with three simple behavioral rules: collision avoidance, velocity matching, and flock centering. Collision avoidance implies the urge to move away from the closest flock members. Velocity matching seeks to match both speed and direction of travel with the rest of the flock. Finally, flock centering urges each bird to move toward the center of the flock. The constant tension between flock centering and collision avoidance is governed by the weights applied to each of the rules until an equilibrium point is reached, effectively prioritizing behaviors differently in critical situations, such as an imminent collision. Reynolds also introduced two other potential behavioral rules: a migratory urge that causes the entire flock to move in a specified direction and a desire to avoid environmental obstacles (Reynolds 1987).

While Reynolds refers to his grouping as a “flock”, his rules tend to produce a disorganized swarm rather than an ordered formation. Nathan and Barbosa modified Reynolds’s rules to attempt to form a V-like formation like those found in nature. They used a visual system and attempted to orient each bird so that it had an unobstructed longitudinal view. Their birds would first seek to establish proximity to another bird within a specified radius. Next they would move relative to the neighbor in order to obtain an unobstructed view. Finally, the birds would move to maintain a specified station relative to the others. This algorithm enabled the birds to transition from position (a) to position (f) in only 200 simulation time steps, as illustrated in Figure 3 (Nathan and Barbosa 2008, 3, 8).

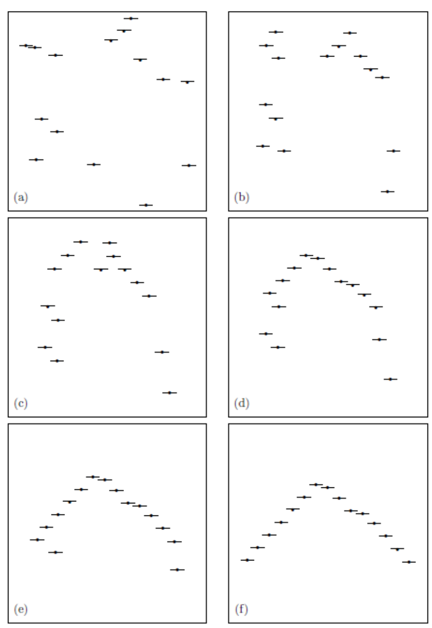


Figure 3: Flocking Algorithm Time-Phased Results

Labonté proposed a similar model with two primary forces. The first force is structure forming and features an attraction between actors until they reach a certain separation distance at which point it becomes repulsive. The second force is navigational and is generated by the UAS's autopilot to follow a proposed course to reach a desired point. Combining these forces enables each to maintain a distinct navigational course when necessary but also includes the urge to form a group. This model presents versatility but is also limited in that the actors do not follow aircraft laws of motion (Labonté 2009, 5-6).

Many other theories, rules, and weighting schemes exist, but the flocking theories all tend to feature various sets of rules which govern acceptable behavior for the individuals within the flock and various techniques for judging which rule is most important for any moment in time. These rules will differ based upon the form and intended function of the flock being constructed. A flock of UASs whose intended function is to provide persistent surveillance over a designated target area will feature different rules than one whose mission is to transport a number of aircraft a long distance. While the specific flocking algorithm varies, it will be clearly shown that many benefits can be gained from finding an algorithm which forms the flock into a "V" formation.

Formation Drag Reduction

While other methods of improving energy efficiency in aircraft design and operations are beginning to plateau because of decades of effort, implementation of research into increasing efficiency through formation flight is still in relative infancy. The concept is borrowed from migrating geese that fly in a "V" formation to reduce overall workload. In aerodynamic terms, the wings of each bird (or aircraft) produce vortices as a result of the pressure difference between the top and bottom surfaces of the wing. This wake turbulence vortex trails behind the aircraft and creates an upwash outboard of the wingtips and a downwash inboard of the wingtips, as illustrated Figure 4 (Cattivelli and Sayed 2009, 50).

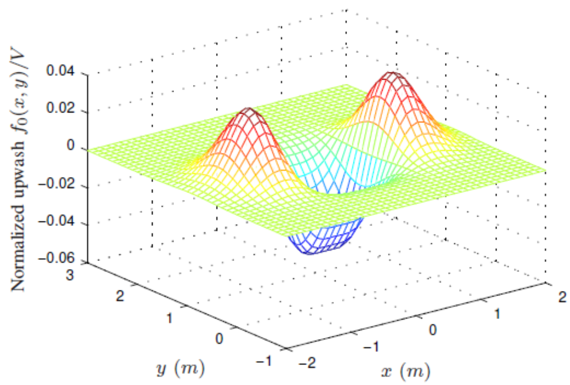


Figure 4: 2-D Upwash Illustration © 2009 IEEE

By positioning a trailing aircraft within the upwash from the previous aircraft, the lift vector of the trailing aircraft is rotated so that lift is marginally increased and induced drag is substantially reduced. While there are other forms of drag, under normal circumstances induced drag comprises approximately 45% of total drag (Ning 2011, 22). Any drag reduction will likely lead to an increase in fuel efficiency. Determining exactly how much the drag is reduced is well beyond the scope of this thesis and lies within the realm of aeronautical engineering and computational fluid dynamics. Significant research into this subject has already been published by many sources and will be referenced as a baseline for simulations in this thesis.

Formation drag reduction research originated in the field of biology. In 1970, Lissaman and Shollenberger calculated that a flock of 25 birds could theoretically achieve a range increase of 71 percent over a lone bird, or more with a tailwind. Additionally, they asserted that the lead bird (tip of the "V") did not actually have the highest workload as long as the "V" had two legs (not a "/" or "echelon") because it could experience the upwash from the birds trailing it. Finally, they postulated a formation where the workload was shared equally among all birds. "The optimal shape of the vee formation, while swept, is not an exact vee; it is more swept at the tip and less at the apex" (Figure 5) (Lissaman and Shollenberger 1970, 1003-1005). Note that if a line were drawn at the average sweep angle through the middle of each leg, both the first and last bird would be behind this line.

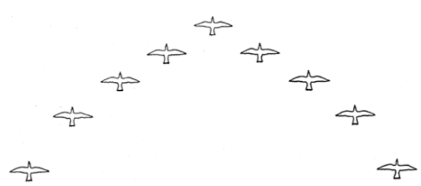


Figure 5: Lissaman and Shollenberger's Theoretical Optimal "V" Formation

Hainsworth expanded upon this research in 1986 by observing actual flocks and comparing their formations with those theoretically proposed by Lissaman and Shollenberger. He shows that most birds trailed one to three wing spans behind the bird ahead of them, though the gap between the lead and second bird was actually wider than subsequent ones, in direct contradiction to Lissaman and Shollenberger's optimal formation. Additionally, he shows that in practice geese achieve a 36% reduction in induced drag, about half of the theoretical maximum, but the geese demonstrate active corrections toward the optimum position (Hainsworth 1987, 459-460).

When transitioning this research from biology to aeronautics, efforts are primarily divided into two categories: close and extended formation. Close formation implies that the streamwise separation between aircraft is very small (in the magnitude of 0-5 wingspans) and is primarily useful for UASs and fighter jets. Extended formation (15-40 wingspan streamwise separation) is more useful for military mobility aircraft or commercial airliners because of FAA requirements and equipment limitations. For extended formation flights, computational fluid dynamics demonstrates that most fuel savings can be maintained even when following distance is increased to 15-40 wingspans, yielding an induced drag reduction of 54% at subsonic airspeeds after accounting for roll moments and trim penalties. Also, the "sweet spot" where 90% of energy benefits can be achieved allows variations of 5% of the wingspan in vertical and 10% in lateral. However, only the trail aircraft experiences drag reduction in the extended formation, as opposed to both aircraft in close formation (Kless, et al. 2012, 1-2).

Close formation presents the potential for greater overall drag reduction but also presents additional challenges due to the increased risk of mid-air collision. NASA's Dryden Flight Research Center has conducted extensive research into close formation flight using both pilot-controlled and autonomous F/A-18s featuring extensive instrumentation for data collection. In 1998 they demonstrated a 10-15% reduction in drag when flying within the vortex, with approximately 20% of available roll authority required to keep the trailing aircraft in position (Figure 6) (National Aeronautics and

Space Administration 1999, 16). They built upon this research by implementing autonomous control techniques to maintain formation position. Using close-coupled guidance and flight control systems they were able to maintain an accurate formation position within 10 cm. Using this autonomous control scheme, NASA was able to demonstrate via flight test that formation flight provides induced drag reduction similar to theoretical models, as seen in Figure 7 (Larson and Schkolnik 2004, 14).

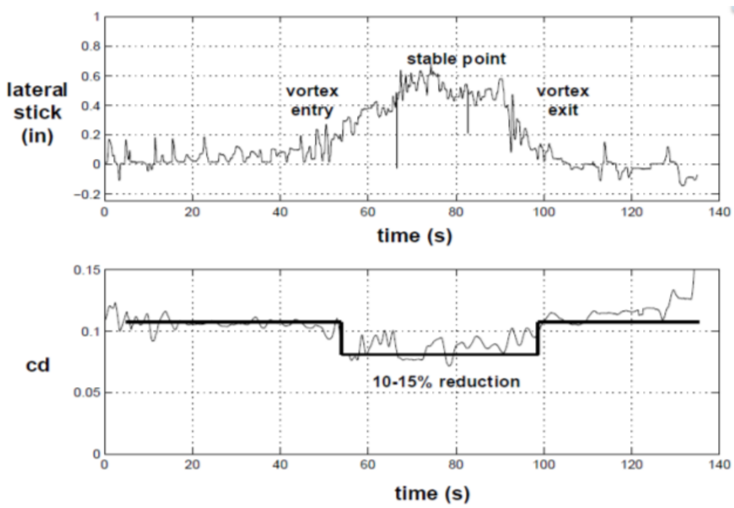


Figure 6: Roll Compensation and Drag Reduction in F/A-18 Formation Flight

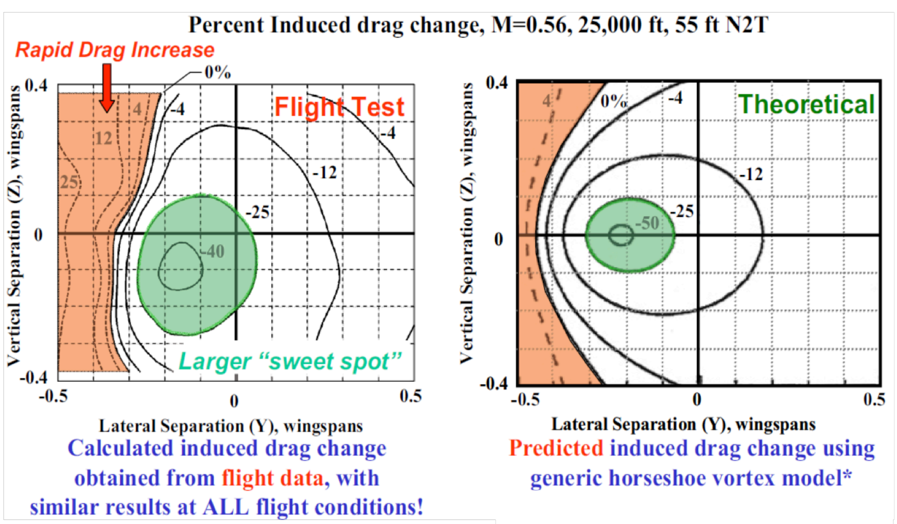


Figure 7: Vortex Influence on Induced Drag

These reductions in induced drag led to demonstrated reductions in overall drag of 20% and reductions in fuel flow of 18%. This study also found that maximum benefit was obtained at the positions shown in Table 1. Values are calibrated to the airplane wingspan *b* and referenced so that (0, 0, 0) indicates aircraft completely overlapping, while decreasing values of X, Y, and Z indicate moving aft, inboard, and down respectively (Vachon, et al. 2003, 29). This study showed no direct benefit in fuel consumption for the lead airplane, but the study did not calculate drag for the lead aircraft and it is possible that these effects were confounded. There is some evidence that points to this conclusion because of a reduction in induced drag benefit for the trail aircraft as longitudinal separation gets smaller than three wingspans, which indicates that the trail aircraft is essentially "pushing" the lead aircraft. One other interesting observation from this study is that the location of the benefit region maintained a fairly predictable location with longitudinal separations up to five wingspans, but began to wander slightly at further aft positions.

Table 1: Region of Peak Drag Reduction Benefit

	Longitudinal (X)	Lateral (Y)	Vertical (Z)
Lower Bound	-3.0 wingspans	0.80 wingspans	-0.10 wingspans
Upper Bound	-4.4 wingspans	0.90 wingspans	0.0 wingspans

In 2002, Eugene Wagner performed a similar flight test and showed 8.8% ± 5.0% fuel savings when flying two T-38 aircraft in close formation (Wagner 2002, 4-1). He also shows that the aerodynamic optimum position predicted by computer models induces a rolling moment which requires flight control deflections to counteract. These flight control deflections increase total drag. In contrast, a slightly different position presents a zero-roll moment which does not require control surface deflection and could potentially cause lower total drag after trim losses are accounted for (Wagner 2002, 1-8). However, pilot experience of trying to fly at the zero-roll moment position proved to be very difficult due to a high degree of dynamic instability (Wagner 2002, 4-12)

Research models do a fairly good job of predicting where wake vortices will exist and the proper relative position to fly to maximize upwash under stable flight conditions. However, a system to detect the vortices would provide a more accurate way to position the aircraft in varying or abnormal flight conditions. Laser-based sensors called “lidar” are capable of detecting and measuring both the wind speeds and pressures associated with vortices (Marks 2005). This technology is mainly being developed for the purpose of avoiding wake turbulence and often intended for ground-based use in the vicinity of airport arrival and departure corridors. The Green-Wake project introduced multiple innovations by developing a fast scanning imaging Doppler Lidar and creating a 3-D visualization of air movement (Bowater 2011). However, the present lidar equipment is quite large and, while useful and appropriately scaled for commercial aircraft, is currently unsuitable for small-scale UASs.

Rather than using lidar to look ahead at wake vortices, Hemati, Eldredge, and Speyer suggest using sensors located on the wing to detect aerodynamic properties of the onrushing air to determine wake location. They assert that the technique used by most studies, using maps of aerodynamic benefit and maintaining a position relative to another aircraft, “can operate reasonably well under ideal circumstances without subjugation to atmospheric disturbances and air craft maneuvers, but they are not robust under more realistic circumstances" (Hemati, Eldredge and Speyer 2012, 2). Their method senses wake signatures using five uniformly spaced wing-distributed pressure sensors to sense difference in airflow across the wing surface. From this information, it uses an iterative approach to repeatedly move in the direction of increasing wake strength until the optimum position is found. Assuming a relatively accurate initial guess (which the aforementioned "maps of aerodynamic benefit" provide), this method should be able to relatively quickly and accurately locate and maintain the optimum position. Overall, the method proved to be fairly accurate in simulation but some estimator biases were observed (Hemati, Eldredge and Speyer 2012). This technique is potentially applicable to the concept of UAS flocking because the instrumentation required for sensing the wake is relatively small and lightweight. The ability to navigate toward an aerodynamic optimum alleviates some of the interplane communication burden because each aircraft is able to "feel" the others rather than just "talking" to them.

For a group of UASs, the close formation position seems to be more appropriate. The tradeoff between the greater drag reduction of close formation (Figure 8) and the simplified collision avoidance of the extended formation introduces an imperative to find an acceptable compromise. Although controllers have been developed that maintain close formation with two aircraft (Ross 2006, 197), the difficulty lies in developing a guidance system that will enable a group larger than two aircraft to maintain this formation while simultaneously reacting to varying atmospheric conditions and mission requirements.

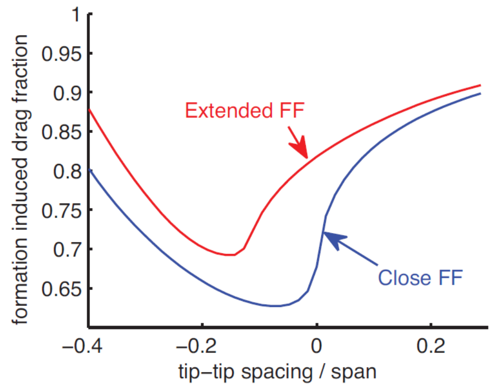


Figure 8: Close vs. Extended Formation Flight (FF) Comparison (Ning 2011, 12)

Guidance Mechanisms

Various techniques have been proposed for controlling a large formation of aircraft with precise station-keeping requirements. The most intuitive and basic approach is for each aircraft to simply maintain the desired position relative to its immediate predecessor. The obvious alternative to this approach is for each aircraft to maintain an appropriately scaled position relative to the overall leader of the formation. Thus if the desired spacing is 10 feet outboard and 20 feet aft of the predecesor, the third aircraft would maintain a position 20 feet outboard and 40 feet aft of the leader. Innocenti et al. refer to these various approaches as Front Mode and Leader Mode respectively, as illustrated in Figure 9. They also show that Front Mode "presents a poorer transient response, due to error propagation" (Innocenti, Giulietti and Pollini 2002, 6). This occurs because Wingman1 is constantly correcting position due to random disturbances or changes to the leader's flight path, while Wingman2 must react to all these changes in addition to its own inaccuracies. This phenomenon is known as string (or accordion) instability: the longer the string of followers grows, the more unstable the station-keeping becomes. Seiler et al. show that the Front Mode will be unstable when using any linear control law but assert that Leader Mode can be implemented because aircraft near the rear are able to anticipate changes and damp out error propagation (Seiler, Pant and Hedrick 2002, 122).

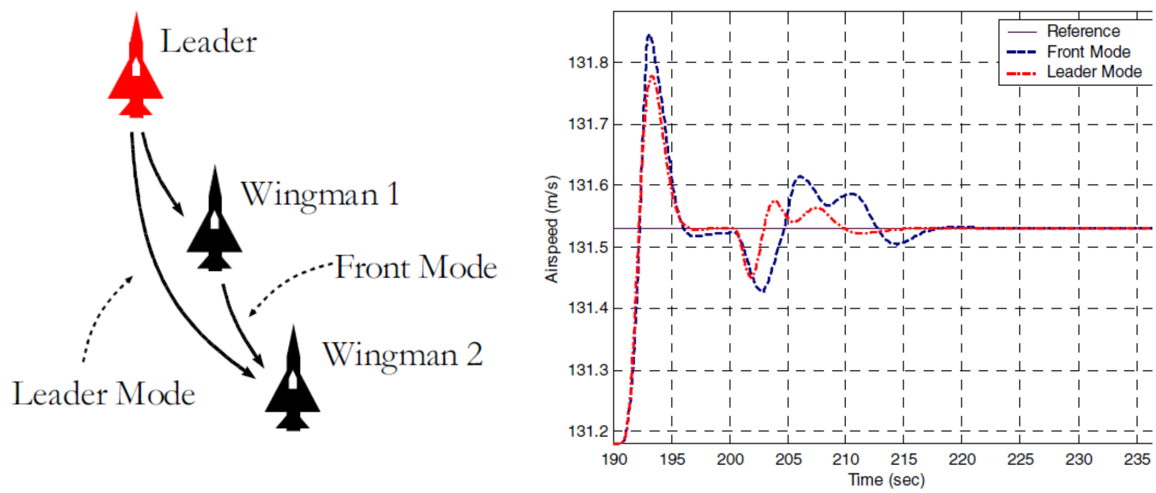


Figure 9: Basic Guidance Control Methodologies and Results

Another potential solution is known as Trajectory Tracking. In this case, all aircraft have a known, planned trajectory and seek to maintain that position at the appropriate time. This guidance approach would be appropriate for either large or small formations when it is desired to fly a prescribed trajectory (Larson and Schkolnik 2004, 19). If the formation navigational controller is able to project its desired location at a set time (say 10 seconds) in the future the rest of the formation can determine the appropriate position to strive for at that same future time. By determining a sequence of these future desired positions a trajectory can be plotted so that other aircraft are able to both join the formation efficiently and maintain a desired relative position. However this method becomes unsuitable if rapid maneuvering is required in response to a threat or changing goal.

Innocenti et al. present an intriguing alternative guidance system that again takes cues from biology. This system, known as Formation Geometry Center (FGC), requires each aircraft to maintain a desired position relative to the geometric center of the formation (Figure 10). This idea is derived from migratory patterns of flocking birds where "if one or more elements of the group loses its position in the formation, the others leave the migration trajectory and 'wait' for the lost ones until the formation shape is reconstituted" (Innocenti, Giulietti and Pollini 2002, 11). If one bird begins to lag in any direction, the formation's geometric center is moved slightly in that direction, causing all the other members of the formation to correct back toward this center point. This guidance mechanism is also easy to adapt to current flocking methodology, as the rule to move to the center of the flock can easily be replaced by a rule to move to a certain position relative to flock center.

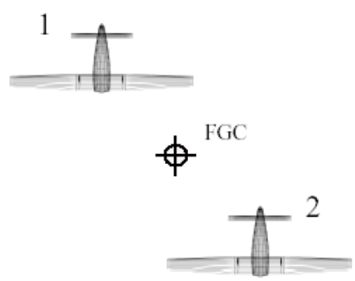


Figure 10: Formation Geometry Center

Mitchell, in addition to discussing these guidance techniques, also mentions other potential guidance strategies which would be potentially more difficult to integrate with this scenario. One is a Neural Network whereby a network is trained to maintain a proper position by comparing inputs and desired outputs. Another is Performance or Extremum

Seeking, where the guidance system senses changes in performance and moves opposite the gradient of the performance function. A third is Vortex Shaping, where variable wing geometry allows the leading aircraft to manipulate its wake so that the vortex moves toward the trailing aircraft instead of vice versa. These guidance approaches will not be used further in this research but are mentioned as possible areas of further research (Mitchell 2005, 8).

Summary

United States Air Force aircraft employ formations to meet a variety of mission requirements, including mutual support, communication, increased persistence, and higher payloads. Flocking provides the ability to increase the size of formations, especially of unmanned aircraft, while requiring a minimum number of manned operators. Close formation flight enables aircraft within a formation to extend each other's range and endurance by utilizing updrafts created. Various control and guidance paradigms are possible to maintain the precise position required to reap the benefits of integrating flocking with close formation flight. By combining all these technologies, new capabilities can be obtained that would be impossible with any of them independently. If these technologies are implemented, the American war fighter will benefit from increased efficiency and decreased operator task requirements.

III. Methodology

Chapter Overview

The flocking model was built using Reynolds's three basic rules as the baseline: collision avoidance, flock centering, and velocity matching. Each rule was modified for the specific requirements to achieve drag reduction from wake vortices. The biggest change was modifying the "navigate toward the center of the flock" rule to "navigate toward a precise position with respect to the Formation Geometry Center." This allowed the simulated flock to maintain precise positions relative to one another even while navigating random waypoints. Tests were performed on various control parameters to determine a configuration which maximized aerodynamic benefits from preceding aircraft wake vortices.

After the model was developed, the flock was sent to fly away as far as possible to determine maximum range and endurance. Multiple tests were conducted with different airspeeds and formation sizes to determine the effect of formation size and other parameters on optimum cruise airspeeds.

Flock Control Logic

The purest implementations of flocking require that each member of the flock make its guidance decisions using only information that would be available to it. In order for each of the members of the flock to be considered "autonomous," they must make their own guidance decisions rather than submitting to the directions of a central command unit. In the case of a biological flock of geese, the current theory is that each goose determines its flight path based only on visual, audio, and aerodynamic information. Nathan and Barbosa therefore limit themselves to only using certain information when developing their simulation (Nathan and Barbosa 2008, 3). In essence, each bird determines its flight path only in reference to its nearest neighbors. As seen in Figure 11, this frequently leads to undesirable formation geometry which is unsuitable for formation drag reduction.

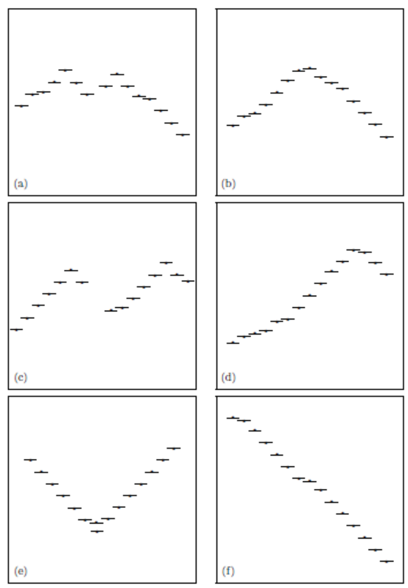


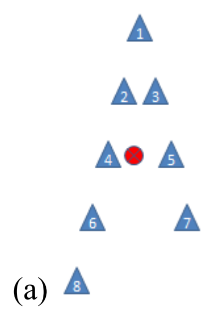
Figure 11: Sub-optimal Flock Guidance Results

In order to experience the aerodynamic benefits from wake vortices, aircraft must maintain precise positions with respect to each other. To accomplish this while promoting overall flock stability, each aircraft requires more information than simply the general location and velocity of its nearest neighbors. In this simulation, the aircraft exchange their current position and velocity during each of the iterations of calculation. This is not a major violation of flocking principles because current technology such as ADS-B allows aircraft to periodically broadcast position, velocity, and altitude information. If the flock is operating in close enough proximity to reap aerodynamic benefits from wake vortices, there are numerous possible methods for exchanging position and velocity information, such as line-of-sight communication or a local area network (Wi-Fi). This enables the flock to operate "semi-autonomously" in that the flock does not require regular guidance or control from a central control unit, but must frequently interact with all other members of the flock. This could also be referred to as cooperative behavior and control.

This simulation uses three general guidance rules based loosely on Craig Reynolds's seminal flocking control methodology: Velocity Matching, Flock Centering, and Collision Avoidance. The largest change from this baseline for this simulation is that rather than moving toward the center of the flock, each aircraft moves toward a pre-defined position relative to the geometric center of the formation. The result of each control rule is then weighted and averaged to provide a desired acceleration for each time step of the simulation.

The Velocity Matching rule is simplest and also encompasses navigation toward the next waypoint in the flock's desired flight plan. The output of the rule is also designed to accelerate or decelerate each aircraft to an aerodynamically optimum airspeed. Since the overarching purpose of integrating flocking with formation drag reduction is increasing fuel efficiency, it is imperative to motivate the flock toward an optimum airspeed when not overridden by other concerns. Because velocity includes both speed and direction, this rule also attempts to turn each aircraft toward a desired direction – in this case the direction from the center of the flock to the next waypoint.

The Flock Centering rule has been extensively modified from Reynolds's methodology to become a Station Keeping rule. Each aircraft assigns itself a formation position number according to the numbering convention of Figure 12a using a function discussed later. The desired spacing between each aircraft is chosen to maximize drag reduction in accordance with Table 1 (in Chapter II). Because the position of maximum benefit actually requires wingtips to overlap, a stagger is introduced to move the aircraft on the right side of the formation aft by half the normal spacing to aid in collision avoidance, as shown in Figure 12b. This is acceptable because drag reduction is much more sensitive to lateral than longitudinal changes (Kless, et al. 2012, 1).



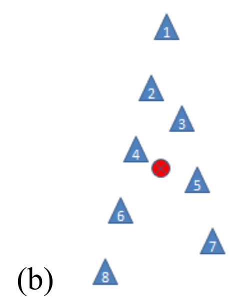


Figure 12: Formation Geometry Center (FGC): (a) Aligned Position (b) Staggered Position

Two other nuances are also incorporated to the Station Keeping rule in order to expedite the join-up process: diminishing lead pursuit and location-dependent action. Lead pursuit is a concept borrowed from dogfighting in aviation, tackling in American football, or any scenario where one body is pursuing another. Rather than point toward where the target is, the interceptor points toward where the target will be. In this case, each aircraft uses the flock's current speed and desired direction to initially look ahead to an aim point 10 seconds in the future, and then adjusts speed and heading to arrive at that point at the same time. As the aircraft closes in on the desired position, the distance that it looks forward is decreased, incorporating desired changes more quickly to avoid stagnation. Specifically, once the aircraft achieves a position within 2 wingspans of its desired position, it shifts to an aim point 6 seconds in the future; once within 1 wingspan of the desired position, it aims 4 seconds in the future. Finally, once within 0.5 wingspans of the desired position it projects only 2 seconds forward. Thus, diminishing lead pursuit acts as a damper, avoiding overcorrections and allowing the flock to stabilize much more quickly. For example, as seen in Figure 13, if aircraft 4 were to turn immediately toward its desired position (red), it would quickly end up pointing too far to the left, overshoot, and end up oscillating back and forth multiple times before eventually stabilizing. Instead, it follows the green path and corrects in a stable and effective manner.

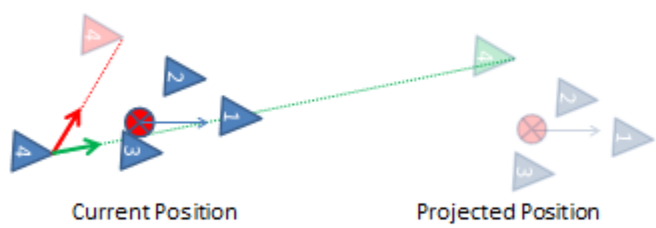


Figure 13: Lead Pursuit

The other nuance used in this rule is location-dependent action. Specifically, the action taken by the aircraft to maneuver to its desired position is dependent on the relative locations of its current and desired position. If the desired position is in the green region shown below in Figure 14, such as aircraft 3 and 4, the previously mentioned diminishing lead pursuit algorithm will be used. Conversely, if the desired position is in the red region, such as aircraft 1, the aircraft will simply slow down and wait for the rest of the flock to "catch up." This is done to prevent drastic overcorrections. Without this provision, aircraft 1 (below) would begin a sharp turn to the right towards its desired position, overshoot, end up performing a complete circle, and find itself at the rear of the flock. This nuance enables the aircraft to maintain a stable flight path and conserve fuel while allowing the rest of the flock to do the majority of the work to establish an optimal configuration. In an intermediate yellow position, such as aircraft 2, the aircraft will slow down and commence a turn toward the desired position, which will quickly move it into the green region.

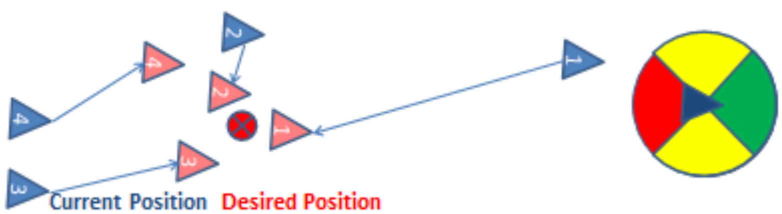


Figure 14: Location-Dependent Action

The third rule, Collision Avoidance, is fairly straightforward. A buffer radius is established, in this case 75% of the desired distance between the number 2 and number 3 aircraft in Figure 12b. If any aircraft are within a region defined by a circle with this buffer radius, current velocities are compared to see if separation distance is increasing or decreasing. If it is decreasing, an immediate evasive turn away and acceleration/deceleration is commanded. Additionally, the input is scaled according to the equation ▯▯▯▯▯ *h*▯=1▯▯▯▯▯▯▯▯▯▯2 so that the closer the intruder is, the more drastic the evasive action will be. One additional nuance is incorporated: if any aircraft is rapidly maneuvering with respect to the rest of the formation, the size of the buffer zone size for that aircraft is increased so that it begins evasive actions earlier. Rapidly maneuvering is defined by having a heading more than a pre-defined number of degrees different from the average heading of the formation. This is necessary because aircraft with large heading differentials move very rapidly relative to the rest of the formation and therefore need to commence evasive actions earlier in order to avoid collisions.

After the results of all three rules are calculated, the rules are combined into a weighted average. Another damper is applied for aircraft that are near their desired position to prevent destabilizing rapid corrections. Next, aerodynamic limitations are applied to each aircraft's proposed turn and acceleration. These limits include:

- Maximum turn rate (related to bank angle and g-limitations)
- Roll rate (change in turn rate unit time)
- Minimum and maximum velocity
- Maximum linear acceleration and deceleration

A fourth function is incorporated at the same time that the other three rules are calculated: at every time step each aircraft determines if it should maintain its current formation position or move to a different position within the formation. Formation position changes are normally initiated after turns in order to reform the proper formation in a minimum amount of time, as illustrated in Figure 15. After the flock geometric center point has passed the target waypoint, each aircraft calculates an angle between two imaginary lines: one going from the flock center point to itself, and another going from the flock center point to the next waypoint. Because each aircraft knows the position of all the other aircraft in the flock, it is able to calculate this angle for each of the other aircraft. The aircraft which determines it has the smallest angle, based on comparing its angle with the others' angles, becomes the new "#1" aircraft, the aircraft which has the next lowest positive value becomes "#2", and the one with the smallest negative value becomes "3", and so on. Observations showed that this is only beneficial for turns of larger magnitude; therefore for turns under a pre-defined number of degrees, all aircraft will maintain their current position. This pre-defined number of degrees is a configurable parameter and will be referred to later as Reposition Turn Angle later in Table 3.

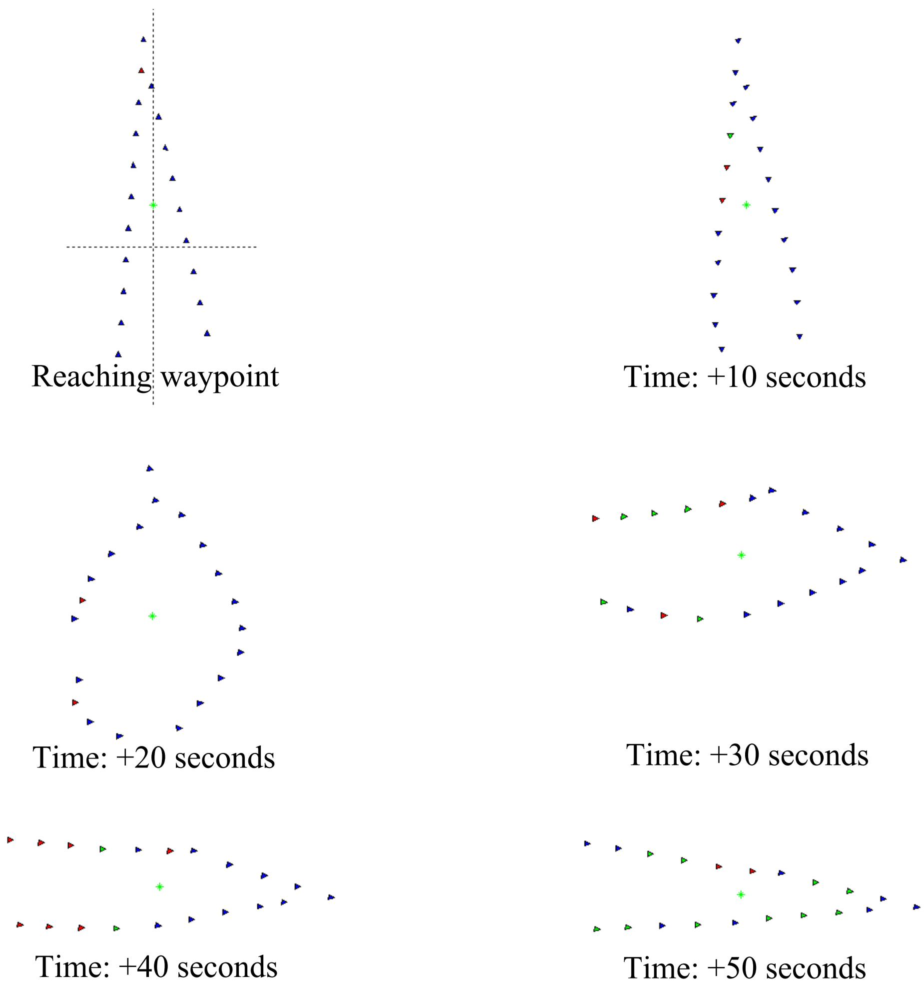


Figure 15: Flock Position Changes

While position changes are normally only initiated after turns, it also makes sense to change positions occasionally during prolonged straight legs. This occurs because the lead aircraft does not reap any aerodynamic benefit with intermediate longitudinal spacing values and will burn its fuel more quickly than the others if it does not have a chance to move to a different position within the formation. Similar to bicycling, the aircraft in the simulation will all rotate one position clockwise if a pre-defined number of seconds elapses without any other position changes. Alternatively, one aircraft could be designated as the “sacrificial lamb” and maintain the lead position at all times. If this aircraft carries additional fuel rather than a payload of sensors or weapons it could absorb the full portion of induced drag while others constantly experienced a reduction in drag. However, the simulation implements the prior model where all aircraft have equal fuel capacity and attempt to distribute the burden of leading equally.

Aerodynamic Calculations

As the aircraft advance throughout the simulation, multiple aerodynamic properties are continuously being calculated. A combination of constant settings (air density, wing area) and variable factors (desired acceleration, wingtip vortex effects) are used to determine the fuel consumption value for every time step of the simulation. In this case, aerodynamic coefficients such as ??0, ε, and S are taken from the Aerosonde UAV. The Aerosonde, with a 2.9 m (9.7 ft) wingspan, is the approximate scale of UAV for which a flocking scenario is deemed to be most realistic. However, it is worth noting that the factors of interest are *relative* fuel savings and drag reduction, not the raw lift/drag/thrust values. For example, this simulation will not attempt to demonstrate accurately what the range of a solo Aerosonde is, but rather show what the relative increase is when multiple UASs fly in an optimum formation. Overall, these coefficients themselves are relatively unimportant and results should, for the most part, be scalable to other airframes of the similar general size and wing shape.

Like many good engineering projects, the calculations begin with a Free Body Diagram and Newton's second law, $F=ma$. Again, as the goal of the thesis is to demonstrate relative gains rather than absolute values, some simplifying assumptions are made when completing the Free Body Diagram (Figure 16). That is, Thrust and Drag forces act purely in the horizontal plane and Lift forces act orthogonal to the direction of flight. These assumptions are fairly accurate in level flight with normal angle of attack values. Since the simulation models level flight, there is no vertical acceleration and

Table 2: Aerosonde UAV Aerodynamic Coefficients (Beard and McLain 2012, 276)

Parameter	Value
m (Zero Fuel Mass)	8.5 kg
S (Planform Wing Area)	0.55 m^2
b (Wingspan)	2.8956 m
ρ (Air Density)	1.2682 kg/m^3
ε (Efficiency Factor)	0.1592
▯▯*0* (Zero-Lift Drag Coefficient)	0.03
g (Gravity Constant)	9.8 m/s^2

therefore lift is equal to weight (*L-W=0*). Using fundamental lift and weight equations:

$$\frac{1}{2}\rho V^2 S C_L \cos\theta = mg \tag{1}$$

Where ρ is *air density*, V is *velocity*, S is *planform wing area*, C_L is the *coefficient of lift*, θ is *bank angle*, m is *mass*, and g is *acceleration due to gravity*.

Because ρ, S, and g are constant throughout the simulation (Table 2), and m, V, and θ are determined in the simulation, Equation 1 is rearranged to calculate C_L.

$$C_L = \frac{2mg}{\rho V^2 S \cos\theta} \tag{2}$$

Next, Newton's second law is used to calculate horizontal forces:

$$T - \frac{1}{2}\rho V^2 S C_D = ma \tag{3}$$

Where T is *thrust required*, C_D is the *coefficient of drag*, a is *linear acceleration*.

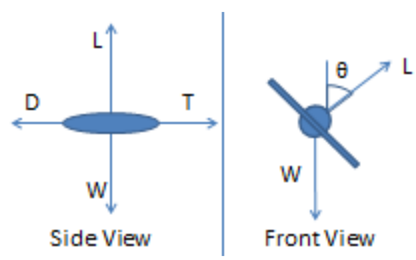


Figure 16: Aerodynamic Forces Free Body Diagram

The drag coefficient is typically broken down into multiple components: skin friction, form, and induced. Skin friction drag and form drag are often combined into one term: the zero-lift drag coefficient C_{D0}, while induced drag is calculated as a fraction of the square of C_L. However, in this case, the induced drag coefficient has an added term because the wake vortices only affect induced drag. Note that C_{DR} is introduced in this thesis, but the rest of these equations are basic aerodynamic equations (Aerostudents 2006). Thus C_D is calculated:

$$\square\square=\square\square 0+\square\square 2\square\square\square 2\square\square\square\square \qquad (4)$$

Where *b* is *wingspan*, *ε* is the *efficiency number*, and C_{DR} is the *coefficient of drag reduction* caused by wake vortices.

Because *b*, *ε*, and $\square\square 0$ are constant throughout the simulation (Table 2) and C_{DR}, *m*, and *a* are calculated every time step, required thrust (*T*) can be computed by combining Equations 2, 3, and 4 to form Equation 5:

$$\square=\square\square+ \quad 12\square\square 2\square\square\square 0+2\square\square \quad \square\square 2\square\cos\square 2\square\square\square 2\square\square\square\square \qquad (5)$$

Fuel consumption is assumed to be linearly related to thrust produced, although this is not necessarily true at extreme throttle settings. Specifically, a specific fuel consumption value of 0.009286 kilograms/Newton·hour is derived from actual performance of an Aerosonde as demonstrated by the *Laima* (McGeer 1999, 22). Fuel consumed is then subtracted from the mass of the aircraft and monitored as the simulation proceeds.

The coefficient of drag reduction (C_{DR}) is not a formal aerodynamic term but instead one invented for the purposes of this simulation. It is derived by combining the research of Vachon et al. with that of Ning (Vachon, et al. 2003, 14, 17), (Ning 2011, 12). Using their research, a table was constructed (see Appendix A) to determine C_{DR} based on lateral and longitudinal offset from preceding aircraft. The simulation simply reads a value from this table based on the relative position of any two aircraft and returns that value as C_{DR}.

Simulation Architecture

The simulation was built using the MATLAB programming language and complete code can be found in Appendix B. The simulation contains a *configuration* function in which nearly all simulation parameters are initialized, such as the size of the flock, appropriate weighting of the flocking rules, the length of time for the time step, desired formation spacing, and aerodynamic properties. Customization and fine-tuning of the flocking algorithm is possible primarily through editing this function. The simulation controller function, named *Main*, serves as the formation controller and directs the sequence of events. After establishing the configuration and initializing other program variables, the simulation begins creating the flock. The flock is launched sequentially at an interval of every few seconds, all originating from the same point at minimum velocity. This simulates an array of launchers that are configured to launch aircraft at a defined time interval. In the simulation, each aircraft is represented by a matrix containing its current position and velocity, turn rate, formation position, color, distance from desired position, and fuel state. Each aircraft also has access to the position and velocity information of the other aircraft, as discussed earlier.

After configuring and initializing the simulation, the main controller enters an iterative loop which represents one time step. Once inside the loop, first the simulation determines whether another aircraft needs to be launched to increase the size of the formation to reach the target size. Next, each created aircraft calculates its next desired move in accordance with the Flock Control Logic mentioned earlier. After the desired move is weighted and controlled for aerodynamic limits, a random noise variable is added to account for turbulence, wind gusts, and other disturbances. Finally, each aircraft actually advances one step in the desired direction.

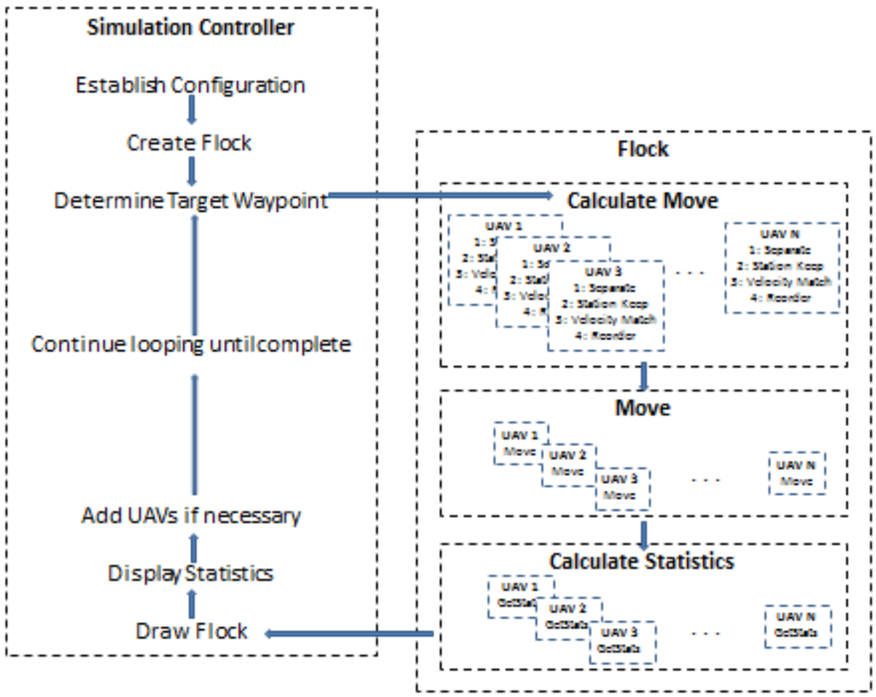


Figure 17: Simulation Architecture

Next, the simulation optionally draws the current position of all aircraft in the formation. This drawing feature can be turned off and run time of the simulation is actually decreased by approximately 90% when it is disabled. Statistics, which will be discussed more thoroughly in the next section, are also calculated and displayed. Finally, the simulation determines whether it is within one “move” of reaching the desired target waypoint. If so, it sequences the flight plan to the next desired target waypoint and the flock will turn. The simulation will run for a pre-defined period of time or until one of the aircraft runs out of fuel, whichever occurs first.

Measures of Performance

In order to assess the effectiveness of the flock's control methodology, measures of performance are defined that show how well the flock is able to maintain the commanded formation and what aerodynamic benefits were achieved.

- Average Distance Out of Position (ft) – a cumulative average for all aircraft of the difference between actual position and desired position,.
- Total Number of Hits (#) – a count of the number of times that the distance from the center of one aircraft to the center of any other aircraft was less than the wingspan of the aircraft, in this case 2.9 m (9.5 ft). Note that this is an overestimation of hits because the non-circular geometry of the aircraft implies that it is possible to meet these criteria without actually colliding, depending on the aspect angle. This does not even account for the potential to incorporate vertical offset in the future.
- Total Number of Near Misses (#) – a count of the number of times that the distance from the center of one aircraft to the center of any other aircraft was less than double the wingspan of the aircraft, in this case 5.8 m (19 feet).
- Cumulative Time in Position (%) – a cumulative average of the percentage of time that an aircraft was within 10% of the commanded position relative to the preceding aircraft, both laterally and longitudinally. This measure excludes the lead aircraft.
- Time to Reach Position (s) – the average amount of time that it took for the entire flock to reform into the commanded formation after each turn. This was defined as when all aircraft reached a position within 10% of the commanded position relative to the preceding aircraft, both laterally and longitudinally. The time was measured when the last aircraft of the flock reached this position.
- Average C_{DR} – A cumulative average of the coefficient of drag reduction experienced by the flock, excluding the lead aircraft. This indicates the fraction of induced drag that was actually experienced by all trailing aircraft.
- Cumulative Fuel Savings (%) – a measure of the percentage difference between fuel consumed versus fuel that would have been consumed if the benefits of wake vortices (C_{DR}) had been ignored.

- Specific Range (nm/kg) – the total distance traveled by the flock divided by the total amount of fuel consumed by the flock.

- Fuel Consumption Standard Deviation (kg) – a measure of the variance between the fuel consumption of all aircraft in the flock. Ideally, all aircraft will consume fuel at an equal rate and this value will be minimized.

Summary

A simulation was built in MATLAB to assess the feasibility of flying a semi-autonomous flock of unmanned aircraft at close enough range to reap drag benefits from preceding aircraft's wake vortices. The simulation includes four basic rules governing the movements of each aircraft: Collision Avoidance, Station Keeping, Flock Navigation, and Formation Positioning. Within these rules are various configuration parameters that fine-tune the effectiveness of the control methodology, which are listed in Table 3 (next chapter). The simulation tracks performance parameters and utilizes aerodynamic benefit data gathered from other research to assess effectiveness. Extensive testing was conducted using different values for the configuration parameters to optimize the formation across 10 Measures of Performance. After determining optimal parameter values, further testing was accomplished to establish the overall success of the designed formation.

IV. Analysis and Results

Chapter Overview

Using a simulation featuring the flock control logic previously discussed, the flock was fine-tuned by applying adjustments to a variety of configuration parameters (Table 3), such as adjusting the sensitivity and magnitude of dampers, the frequency of changes in formation positions, and how often the desired acceleration is calculated. The fine-tuning process began with a broad screening experiment and moved on to individually adjusting configuration parameters to optimize the previously discussed measures of performance (MOPs). A delicate balance was required to weigh the competing interests of minimizing collisions and decreasing fuel consumption. Next, experiments on mission-specific parameters were conducted to determine what missions are better suited toward flocking operation. Finally, two unique mission scenarios were constructed to analyze how a flock, which integrates formation drag reduction, increases performance relative to a flock which does not take advantage of wake vortices. Overall, the flock which uses formation drag reduction demonstrates an ability to increase endurance by 14.5%.

Simulation Assumptions

Significant assumptions are made in the control mechanism that must be either realized or accounted for before the system can be fielded. First, all aircraft are accurately aware of both their own position and the position of other aircraft in the flock every iteration (one second). Sufficient technology already exists to exchange this information within a limited distance, but it is undetermined whether it functions with the needed frequency and accuracy. Also, aircraft in the simulation are able to calculate a vector to their desired position every iteration and immediately apply a desired acceleration (within certain aerodynamic limits) to achieve that position. Computing power isn't the issue; a basic desktop computer was able to compute many acceleration vectors per second in addition to the other calculations inherent in the simulation. Control lag and engine spool-up times have not been accounted for and may not be able to respond to control inputs with the frequency assumed in the simulation.

Despite these assumptions, the simulation also features a major strength to offset these potential weaknesses. Under most conditions, the aircraft are able to avoid collisions in the 2-D environment, although aircraft actually operate in 3-D. It is much easier to achieve collision avoidance in a 3-D environment because aircraft are capable of de-conflicting vertically during rapid maneuvering and then returning to the same vertical plane after stabilizing at or near the desired horizontal position. Additionally, observation showed that most collisions in the simulation occurred not when two aircraft initially got too close, but when one aircraft maneuvered so rapidly in response to the proximity of a second aircraft that it ended up hitting a third. If the response was changed to a primarily vertical de-confliction, the possibility of secondary collisions would decrease drastically.

Screening Experiment

An initial simulation was conducted to determine relationships between various configuration variables and the Measures of Performance (MOPs). The statistical analysis software program JMP was used to design a screening experiment using 19 factors (configuration variables) shown in Table 3 below and 9 responses (the MOPs), discussed in Chapter III. A fractional factorial design was used of order 2^{19-13}, plus a center point, equaling 65 test conditions (2^6+1). Higher order effects were confounded, but all main effects and many two-factor interactions were available. Each test condition was replicated 11 times, for a total of 715 runs. Each test run consisted of two hours of simulated flight between randomly generated waypoints. The test runs each required between 2 and 20 minutes of real time to run, largely dependent on Flock Size and Time Step, for a total of 72 hours run time for the screening experiment. Additionally, the random variables were "seeded" across each replicate, so that, for example, the third replicate at each test condition experienced the same "random" waypoint sequence and wind gusts. This seeding served to control the test so that one configuration would not face more difficult conditions (such as repeated 170-degree turns) than others.

The focus of the screening experiment was not to determine optimum values for each of the configuration variables, but rather to determine which parameters affect which MOPs and the relative strength of these effects. Later testing was planned to optimize each of the configuration variables. It is unreasonable to expect that optimum values were selected during the screening experiment, especially since each parameter was screened at only three levels. Instead, the screening experiment would yield an initial starting point for configuration parameters and a suggested order of optimization.

The last three parameters shown in Table 3 are not really configuration settings but more like mission-dependent variables. For example, the size of the flock is a user requirement that depends on the specific mission, the payload of the individual aircraft,

Table 3: Configuration Parameters in Screening Experiment

Parameter	Values	Description
Cruise Velocity	50, 60, 70 knots	Target velocity for flock during cruise flight
Lateral Spacing	.85, .9, .95 wingspans	Desired position of aircraft with respect to the aircraft preceding it
Longitudinal Spacing	3, 6.5, 10 wingspans	
Time Step	0.5, 0.75, 1.0 sec	Simulation iteration frequency for calculating movements
Rotation Interval	150, 300, 450 sec	Frequency aircraft will rotate position to share burden of being lead aircraft
Reposition Turn Angle	30, 45, 60 degrees	Minimum turn angle where aircraft will reposition to optimize reformation time
Overall Damper Width	1.5, 2, 2.5 wingspans	Damper to commanded movements when within X wingspans of desired position (promotes stabilization)
Overall Damper Magnitude	0.2, 0.4, 0.6	
Separation Margin	0.75, 0.85, 0.95	Fraction of desired spacing between aircraft under which Rule 1 (collision avoidance) becomes active
Rule 1 Damper Angle	10, 15, 20 degrees	Radius of collision avoidance buffer zone established by previous parameter is multiplied by Y when aircraft heading differs from flock average heading by more than X degrees
Rule 1 Damper Magnitude	1.5, 2.0, 2.5	
Rule 1 Leading Damper	0.25, 0.50, 0.75	Damper applied to acceleration commands caused by another aircraft encroaching from behind. Primary responsibility for collision avoidance falls on closing (trailing) aircraft
Rule 2 Damper Angle	30, 45, 60 degrees	Rule 2 (station keeping) is dampened when aircraft heading differs from heading to next target by more than X degrees. Cedes priority to Rule 3 after passing waypoints
Rule 2 Damper Magnitude	0.25, 0.50, 0.75	
Rule 3 Damper Angle	10, 20, 30 degrees	Rule 3 (navigation) is dampened when aircraft heading differs from heading to next target by less than X degrees. Cedes priority to Rule 2 once near desired heading
Rule 3 Damper Magnitude	0.25, 0.50, 0.75	
Leg Length	1, 3, 5 nm	Distance between waypoints (turns)
Generation Interval	0.5, 1.0, 1.5 sec	Spacing between aircraft when initially launched
Flock Size	5, 10, 15	Number of aircraft in flock

and the resources available. This also holds true for leg length and, to some degree, generation interval. Therefore, learning that leg length is the most influential parameter in determining average Coefficient in Drag Reduction is not particularly helpful in configuration selection. It does follow common sense that the flock will be able to take advantage of wake vortices more effectively when flying longer straight legs, but this is not always possible due to mission requirements. However, this information is of value because it illuminates the fact that more resolution will be available on how well the flock maneuvers into position with smaller values for leg length, whereas larger values of leg length will provide better information on how the flock performs after achieving its desired formation.

Many of the effects are confounded in the broad factor screening simulation, but one particular effect was noticed. It was expected that a flock of 15 aircraft would have a vastly larger number of hits and near misses than the flock 5 aircraft. This was because the number of possible interactions between aircraft in a 15-aircraft flock is $152=105$, whereas the number of possible interactions between aircraft in a 5-aircraft flock is only $52=10$. With over 10 times as many possibilities for collision, it is very surprising that the screening experiment results shown in Figure 18 indicated that the number of hits barely doubles when flock size increases from 5 to 15, and the number of near misses is largely unaffected. However, both the bimodal grouping at flock size 15 in the near misses plot and the low values at the center point (flock size = 10) indicate there are other significant factors at play which are confounding the result. One possible explanation for the similar number of near misses despite increase in flock size is that most interactions and near misses occur near the front of the flock, where aircraft are spaced much closer together (Figure 15). This led to the conclusion that the factor optimization experiments could be conducted with a 5-aircraft flock and still reveal most control methodology issues which would cause collisions and near misses. Although the flock control parameters would be optimized while using a 5-aircraft flock, increasing the number of aircraft due to user requirements should not have a drastic effect on collisions and near misses. The screening experiment also showed that changing flock size did not have a large effect on any of the other MOPs. This was particularly beneficial because simulation runtime for the 15-aircraft flock was approximately 10 times as long as the 5-aircraft flock because so many more interactions needed to be calculated.

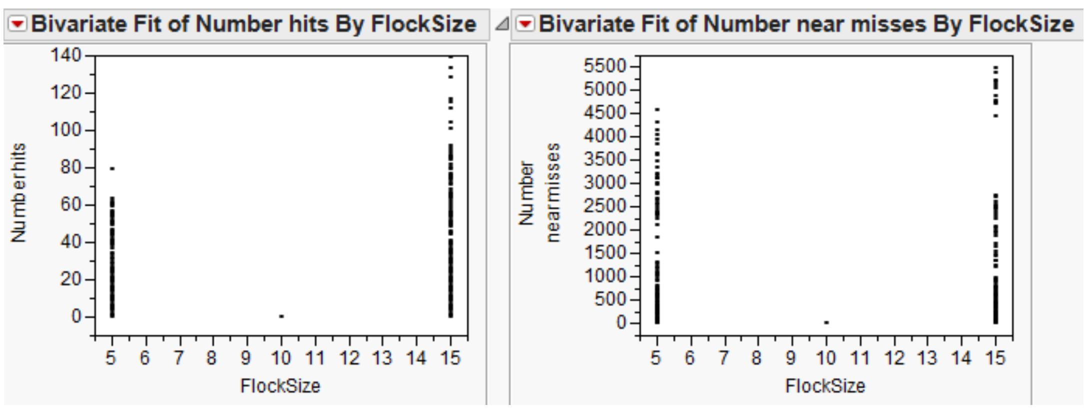
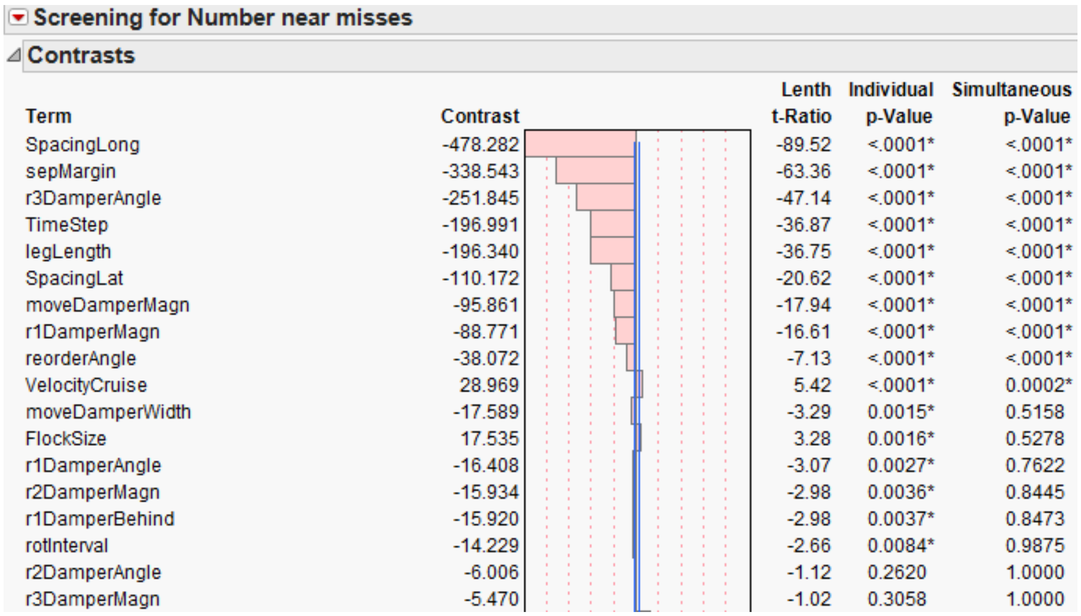


Figure 18: Screening Experiment Results for Number of Hits and Near Misses vs. Flock Size

Iterative Parameter Selection

After running the screening experiment to determine the relative importance of each configuration parameter on the measures of performance, a series of single factor experiments was performed to determine final values for each configuration variable. The screening experiment was used to provide an initial value for parameters and suggest a logical order for the iterative parameter selection experiments. As shown in Figure 19, the screening experiment showed that Longitudinal Spacing (referenced as SpacingLong in Figure 19 and also known as streamwise, nose-to-tail, or fore-aft spacing) had the largest impact on both the number of collisions between aircraft and near misses; therefore it was used for the first iteration. The other factors shown in Figure 19 are explained in Table 3.



Screening for Number near misses

Contrasts

Term	Contrast	Lenth t-Ratio	Individual p-Value	Simultaneous p-Value
SpacingLong	-478.282	-89.52	<.0001*	<.0001*
sepMargin	-338.543	-63.36	<.0001*	<.0001*
r3DamperAngle	-251.845	-47.14	<.0001*	<.0001*
TimeStep	-196.991	-36.87	<.0001*	<.0001*
legLength	-196.340	-36.75	<.0001*	<.0001*
SpacingLat	-110.172	-20.62	<.0001*	<.0001*
moveDamperMagn	-95.861	-17.94	<.0001*	<.0001*
r1DamperMagn	-88.771	-16.61	<.0001*	<.0001*
reorderAngle	-38.072	-7.13	<.0001*	<.0001*
VelocityCruise	28.969	5.42	<.0001*	0.0002*
moveDamperWidth	-17.589	-3.29	0.0015*	0.5158
FlockSize	17.535	3.28	0.0016*	0.5278
r1DamperAngle	-16.408	-3.07	0.0027*	0.7622
r2DamperMagn	-15.934	-2.98	0.0036*	0.8445
r1DamperBehind	-15.920	-2.98	0.0037*	0.8473
rotInterval	-14.229	-2.66	0.0084*	0.9875
r2DamperAngle	-6.006	-1.12	0.2620	1.0000
r3DamperMagn	-5.470	-1.02	0.3058	1.0000

Figure 19: JMP Output: Screening Experiment, Number of Near Misses

To determine an optimum value for Longitudinal Spacing, eight separate values were tested with 5 replicates each, with each test point lasting 10 simulated hours. Examination of the C_{DR} lookup table (Appendix A) revealed that a local minimum occurred at 6.5 wingspans, so that value was tested in addition to other, whole number values. All other configuration parameters were held constant at the starting point suggested by the screening experiment. The MOPs were compiled into the average table shown in Table 4 and compared to each other. From here, a strict comparison of values is influenced by subject matter expertise to determine which value to select. Of the

MOPs below, Numbers of Hits and Near Misses are considered most important because all the fuel savings are useless if the aircraft collide. Of the remaining variables, Average C_{DR}, Cumulative Fuel Savings, and Specific Range are considered more important because they are first-order measures of how well the flock is reducing its fuel consumption. In contrast, time in position, Distance Out of Position, and Time to Reach Position are secondary MOPs that are not direct indicators of benefit, but rather measures that can be used to diagnose potential causes for poor values of first-order MOPs.

Table 4: Longitudinal Spacing Factor Optimization Results Comparison

Longitudinal Spacing (Wingspans)	Fuel Consumption Standard Deviation (kg)	Time in Position (%)	Distance Out of Position (ft)	Number Hits	Number Near Misses	Time to Reach Position (s)	Average CDR	Cumulative Fuel Savings (%)	Specific Range (nm/kg)
	Minimize	Maximize	Minimize	Minimize	Minimize	Minimize	Minimize	Maximize	Maximize
4	0.0023	74.05	5.53	0	26.2	39.30	0.74	6.79	423.01
5	0.0026	73.22	6.88	0	2	45.32	0.741	6.71	422.18
6	0.0025	73.61	7.80	0	0	43.22	0.714	7.45	426.37
6.5	**0.0028**	**72.58**	**8.40**	**0**	**0**	**45.04**	**0.709**	**7.58**	**427.33**
7	0.0023	71.80	9.50	0	0	47.32	0.713	7.48	425.83
8	0.0031	70.81	10.61	0	0	47.03	0.724	7.20	424.92
9	0.0025	68.90	12.14	0	0	48.42	0.735	6.90	423.75
10	0.0029	66.69	13.22	0	0	49.94	0.745	6.64	422.64

From the Longitudinal Spacing results, it was difficult to determine which value to use, because some factor settings performed better at some responses but not others. 7.0 wingspans performed best at minimizing Fuel Consumption Standard Deviation, 5.0 wingspans performed best at minimizing Distance Out of Position, and 6.5 wingspans performed best at maximizing Cumulative Fuel Savings. In this case, a more detailed examination of the data was required. JMP was used to fit a second order model to each factor. As shown in Figure 20, the results for Fuel Consumption Standard Deviation were much more spread out and less statistically significant ($R^2 = 0.027$) whereas the data for Cumulative Fuel Savings conformed more closely to the curve and are statistically significant ($R^2 = 0.606$). For this reason, 6.5 wingspans was selected as the value for Longitudinal Spacing for all subsequent trials.

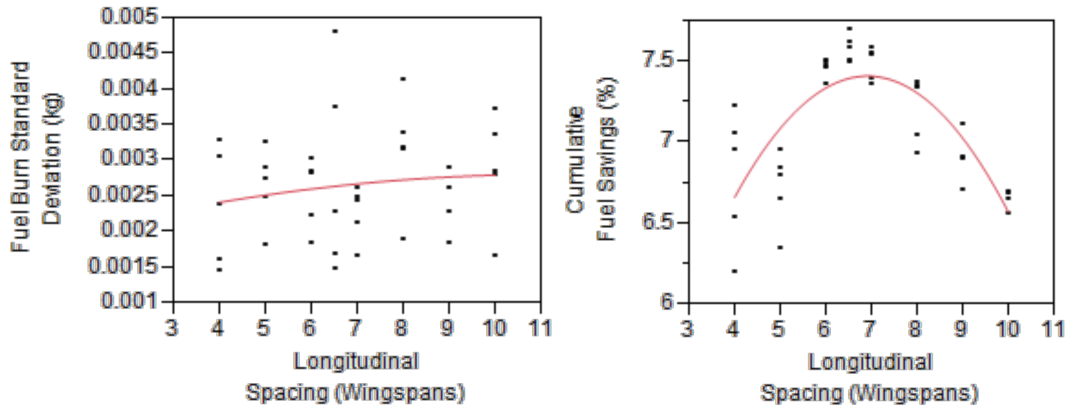


Figure 20: JMP Regression Plots for MOPs vs. Longitudinal Spacing

For some factors, interaction effects were obvious and could not be ignored, making a single factor analysis illogical. For example, each of the rule effect dampers was composed of both a criterion when the damper became effective and an amount that the response was dampened. For factor pairs such as these, two individual single factor analyses were conducted first to optimize each factor individually. After that, a 3^2 full factorial design was used, with the previously calculated optima as the center. This allowed interaction effects to be analyzed and accounted for, to a limited degree. This process was repeatedly iteratively until optimal values were determined for all configuration parameters, as shown in Table 5.

Table 5: Results of Iterative Parameter Selection Experiment

Parameter	Optimum Value
Cruise Velocity	55 knots
Lateral Spacing	0.9 wingspans
Longitudinal Spacing	6.5 wingspans
Time Step	1.0 seconds
Rotation Interval	240 sec
Reposition Turn Angle	10 degrees
Overall Damper Width	2.0 wingspans
Overall Damper Magnitude	0.45
Separation Margin	0.75
Rule 1 Damper Angle	15 degrees
Rule 1 Damper Magnitude	1.5
Rule 1 Leading Damper	1
Rule 2 Damper Angle	35 degrees
Rule 2 Damper Magnitude	0.30
Rule 3 Damper Angle	30 degrees
Rule 3 Damper Magnitude	0.20
Generation Interval	1.0 sec

Flock Performance

After optimizing the simulation, a flock of 10 aircraft flying at 55 knots demonstrated an ability to increase performance even when making 90 degree turns every 0.8 nautical miles, as shown in Figure 21. Each data point on Figure 21 represents the average of three trials, between which was a very low spread (the mean of the standard deviations was 0.06%), indicating a high degree of confidence in the results. For turns spaced at intervals less than this, trailing aircraft will spend more time in the downdraft from preceding aircraft, decreasing performance. At turns spaced further apart, performance continues to increase steadily until asymptotically approaching a fuel savings of 13-17%, depending on flock size. One reason that maximum fuel savings increases with flock size is because the relative contribution of the lead aircraft (which always has a fuel savings of 0%) diminishes as more aircraft are added to the flock. The minimum turn length, or minimum orbit size, increases as flock size increases and also decreases accordingly with flock size. Although this information was only demonstrated and calculated at airspeed of 55 knots, similar computations could be performed at other airspeeds as desired when time allows.

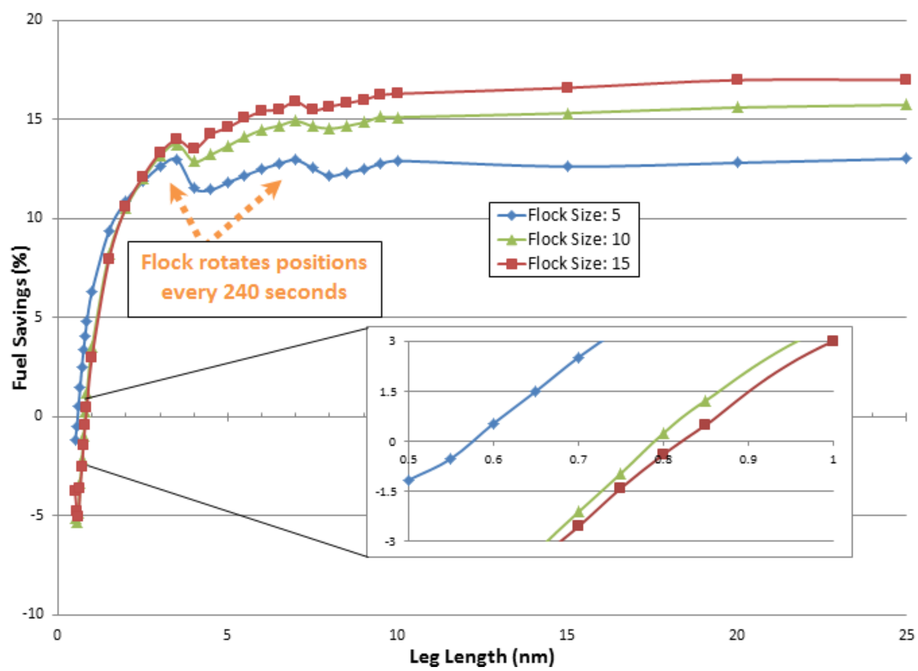


Figure 21: Flock Cumulative Fuel Savings vs. Distance Between Turns

This data provides insight into how to more effectively utilize the flock in an operational mission situation. If a mission requires the flock to orbit around a fixed point on the ground at a small radius, which can be approximated by flying a square pattern, the wake turbulence drag reduction formation may not be beneficial. Two key crossing points are evident: one point where it is more beneficial to split into individual aircraft and another where it is beneficial to split into smaller flocks. The first crossing point occurs where each curve intersects the horizontal axis, at leg lengths between 0.5 and 0.9 miles. For turns more frequent than this, it is more advantageous to split up the flock. The second crossing point, where large flocks become more beneficial than small flocks, occurs when leg length is greater than about 2.5 miles. If a flock of 15 aircraft were desired to fly a square pattern with side length of 0.7 miles around a fixed point, it would actually be more beneficial to split the flock into 3 separate flocks of 5 aircraft. This would yield a 2.5% fuel savings rather than a 2.5% fuel penalty, as shown in Figure 21(inset). Therefore, smaller flocks are more beneficial when making frequent turns, with larger flocks becoming more beneficial for leg lengths above approximately 2.3 miles.

Mission Scenario Analysis

After determining which configuration parameters have the largest effects on flock performance, optimizing these configuration parameters, and testing the flock's ability to make continuous turns, the flock was sent to conduct two different sample missions. The first mission (Figure 22) consisted of a long-distance transit to a target area, an extended time orbiting this area, and a return to base. The mission specifies a unique collection of sensors, one carried by each aircraft in the flock. By using relatively cheap unmanned aircraft, effectiveness can be increased drastically because adding a capability is as simple as adding another aircraft to the flock. As an added benefit, each aircraft added to the flock increases the fuel efficiency of the other aircraft. While this scenario illustrates just one possible reconnaissance mission, the flock could be configured to accomplish most missions currently flown by USAF reconnaissance aircraft (convoy route scan, friendly force overwatch, target pattern-of-life development, battle damage assessment), in addition to others that are currently impossible. Other aircraft types could also be added, such as a fighter, bomber, or tanker. Ultimately, the possibilities are only limited by the imagination.

Mission Description:	**Payload Composition**:
Launch flock of 10 aircraft from home base and proceed to suspected bed-down location of high value target. Using cross-cueing of various intelligence collection suites, attempt to locate target and determine who else is in the vicinity. Orbit for up to 24 hours if necessary. If no civilians are present, provide laser designation for precision kinetic strike from another aircraft. Return to base.	1 Wide visual spectrum camera 1 Narrow visual spectrum camera 1 Wide infrared camera 1 Narrow infrared camera 1 ELINT collection suite 1 MASINT collection suite 1 COMINT collection suite 2 Beyond-Line-of-Sight comm relays 1 Laser designator/rangefinder

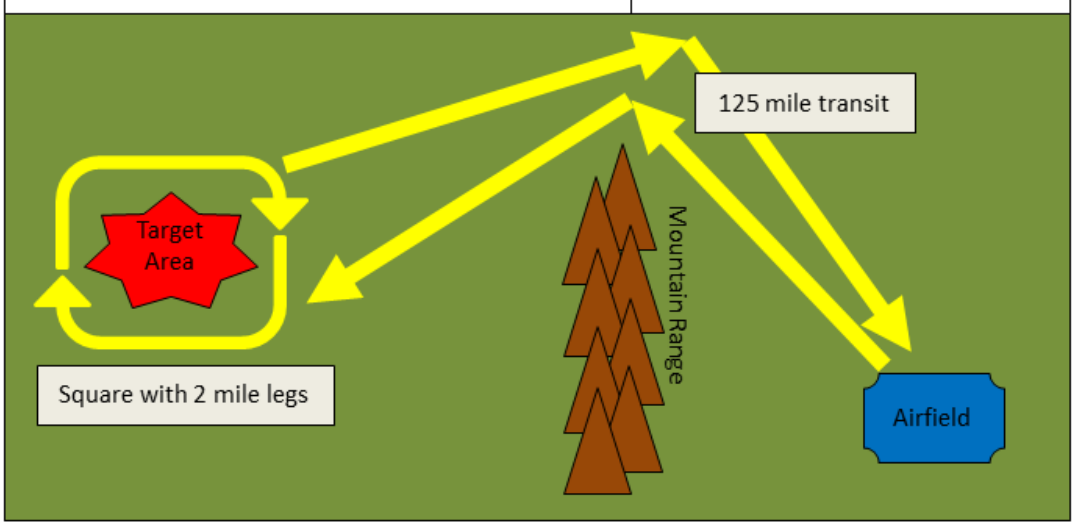


Figure 22: Hypothetical Mission Scenario One – Target Surveillance

The flock was able to complete the first scenario successfully at airspeeds ranging from 45 to 75 knots, taking an average of 28.4 hours to accomplish the mission (24 of which were orbiting the target area). Throughout the 597 total hours of simulation time, only one collision was assessed to have occurred. Although this sounds bad, the hits assessed in the simulation are an overestimation of actual collisions and could potentially be avoided through vertical maneuvering. Additionally, the mission profile was accomplished three times with only one aircraft in the flock to provide an approximation for fuel consumption if the 10 aircraft required for the mission operated independently and maintained sufficient distance between them to avoid any effects of wake vortices. Overall, the flock experienced a fuel savings of up to 14.2%, depending on cruise airspeed.

Fuel savings in itself is not the best measure of performance, as both the flocking and non-flocking aircraft were able to accomplish the mission, the flocking aircraft simply returned home with more gas in the tank. The true benefit lies in calculating how long the flock could extend its orbit over the target area. Assuming that the aircraft desired to land with a fuel reserve equal to 5% of total fuel capacity, a non-flocking aircraft flying at optimum airspeeds could maintain the target orbit for 31.9 hours, while the flock could maintain the orbit for 36.6 hours, a 14.5% increase in orbit endurance.

Fuel consumption was compared for the three distinct phases of the mission: transit to the target area, orbit over the target, and transit from the target back to base. Figure 23 highlights an important distinction between best range and best endurance airspeeds. Best range speed is advantageous during transit to and from (Figure 23a and c), whereas best endurance speed is optimal when maintaining an orbit for an extended period of time (Figure 23b). It is also worth noting that the best range speed for the flock of 10 aircraft is approximately 5 knots slower than the best range speed for a single aircraft. This occurs because the wake vortices only affect induced drag, leaving parasite drag unaffected. This causes changes in the drag curves as illustrated in Figure 24. Note that the red lines in the figure indicate best endurance airspeed; best range airspeed is approximately 15 knots faster in this case.

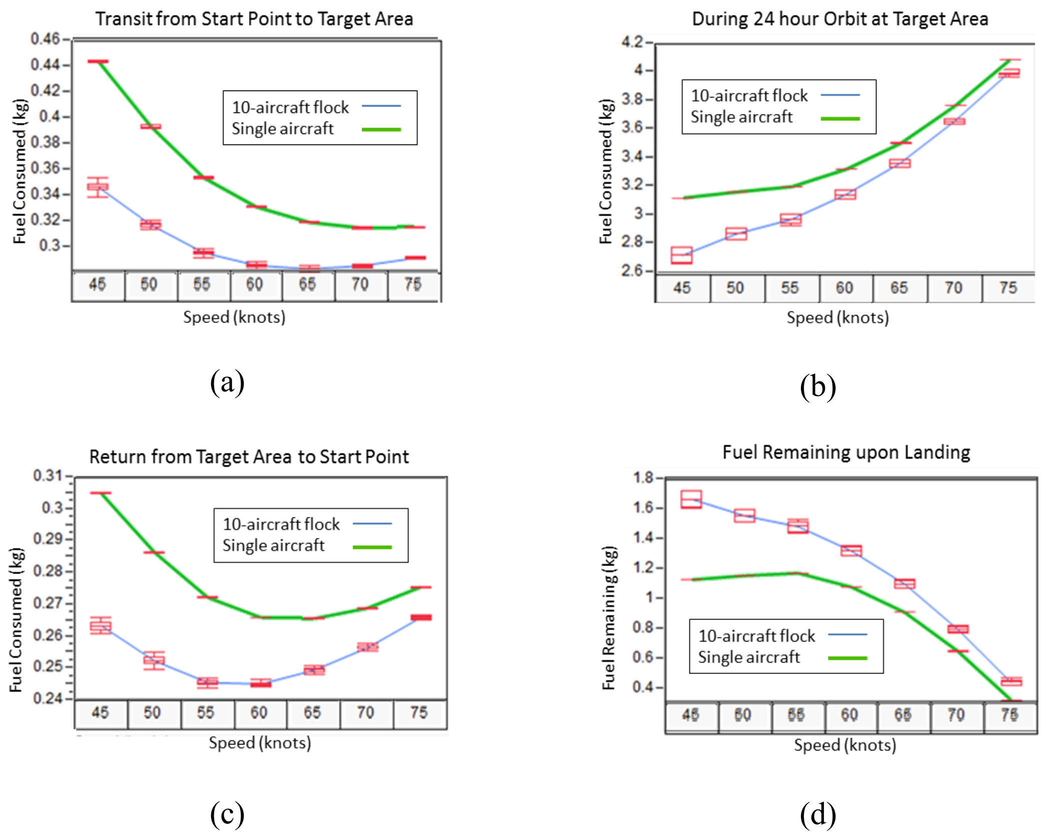


Figure 23: Variability Charts for Fuel Consumption at Different Stages of Scenario One

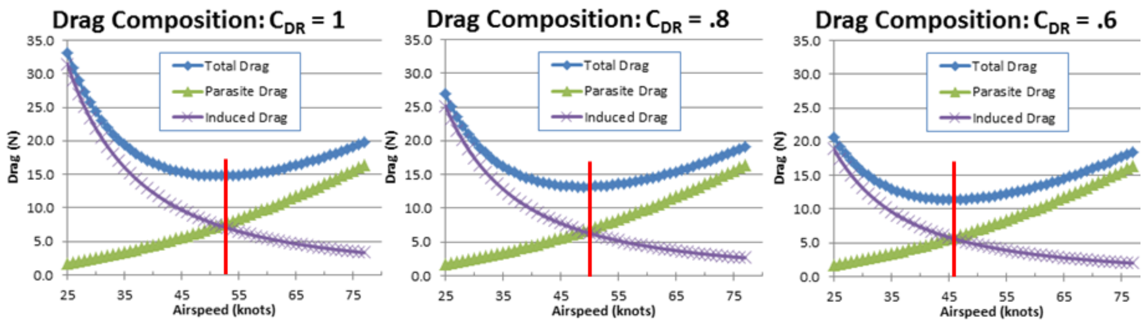


Figure 24: Drag Composition at Various CDRs

A comparison of Figure 23a and c shows that best range airspeed (minimum fuel consumption) is significantly faster at the beginning of the mission than at the end, after mass has decreased significantly due to fuel consumption. This effect also occurs because mass only affects induced drag. With a decrease in mass close to 30%, best range airspeed decreases by about 10 knots for this aircraft.

Because the best range airspeed for the flock is 65 knots and best range for an individual aircraft is 72 knots, one might mistakenly assume that though the flock is more efficient, the single aircraft can accomplish the mission more quickly. This is inaccurate because the flock is still more efficient than the single aircraft at all airspeeds, even 72 knots. However, the benefit margin decreases as airspeed increases. Again, this is because the fraction of total drag caused by induced drag is smaller at higher airspeeds. At 75 knots, the observed fuel benefit was only 2.9%, but at 45 knots the fuel savings increased to 14.2%.

The second mission (Figure 25) augments the previous military scenario by demonstrating the usefulness of the flock in a civilian scenario. In this case, data on active wildfires is desired to properly direct fire-fighting efforts. Other potential scenarios abound, such as searching for lost hikers or surveying damage from natural disasters. By utilizing a flock of five aircraft, multi-spectral imaging can be achieved on every pass, allowing data to be collected at the same time and correlated across the different spectrums. Additionally, by working as a formation and taking advantage of drag reduction, the flock is able to increase its area coverage for every mission.

The results for Scenario Two were very similar to Scenario One with only one predictable exception: the optimum speed over the target area was much higher for

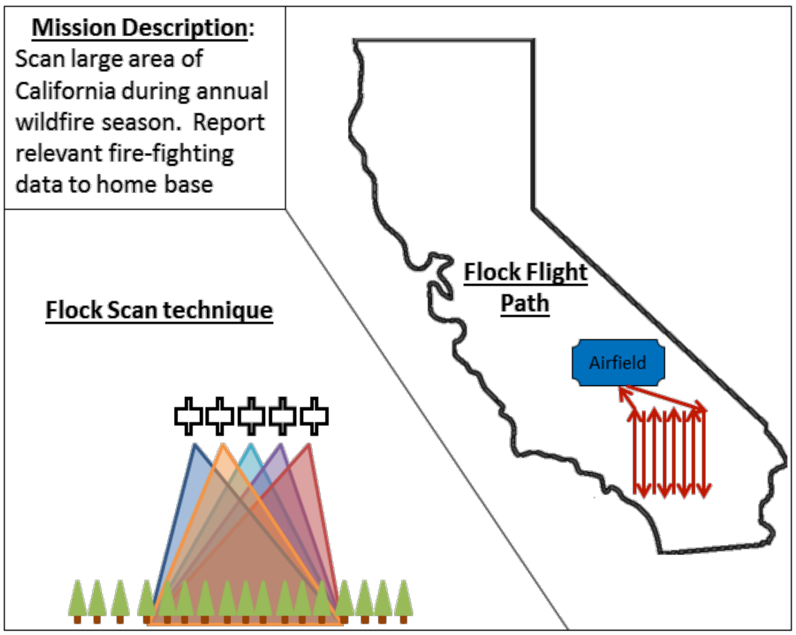
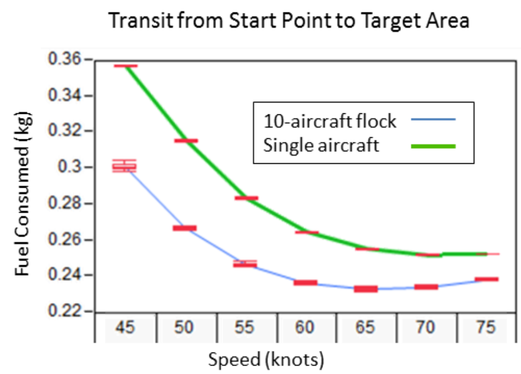


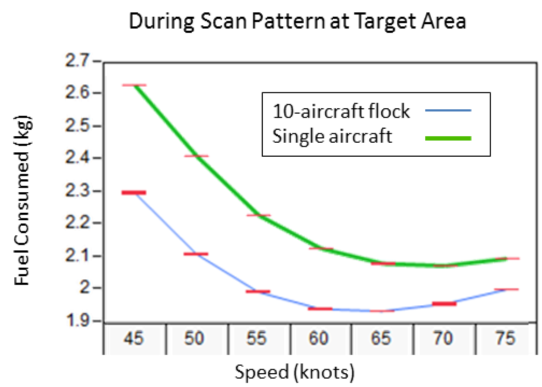
Figure 25: Hypothetical Mission Scenario Two - Area Scan

Scenario Two than Scenario One. This occurred because Scenario One required maintaining an orbit over a designated geographical area for a defined amount of time (best endurance) whereas scenario 2 required traveling a designated distance while utilizing sensors (best range). As seen in Figure 26, the other major observations from scenario 1 still apply to this scenario. The flock outperforms the single aircraft in all phases of flight and at all speeds, though notably more so when slower and heavier.

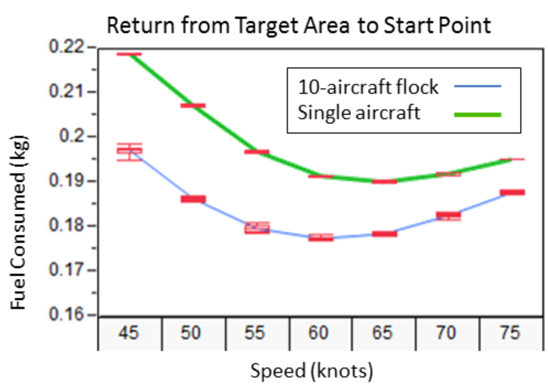
Slower optimum speeds are still evident in all phases, though by a somewhat smaller margin. Overall fuel consumption at the optimum flock airspeed, 65 knots, was 7.3% less than for non-flocking aircraft, which equates to an 8.1% increase in square mileage covered per flight.



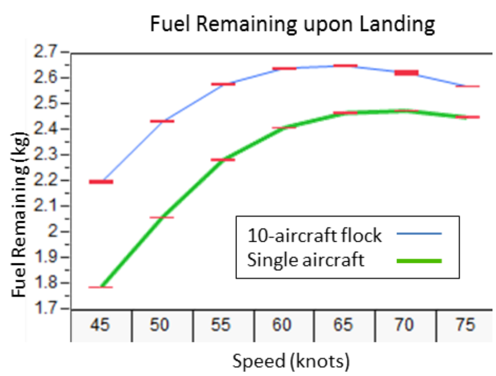
(a)



(b)



(c)



(d)

Figure 26: Variability Charts for Fuel Consumption at Different Stages of Scenario Two

Summary

After constructing the general simulation to allow a flock of aircraft to semi-autonomously maintain relative spacing to take advantage of wake vortices, a variety of experiments were conducted to optimize the flock. The first broad screening experiment featuring high and low values for a variety of flock and configuration parameters was used to determine which configurations affected which measures of performance and by how much. This experiment laid the foundation for the second series of experiments, where factors were individually optimized. After determining optimum values for parameters which were not mission-dependent, testing was accomplished at different values for mission-dependent variables to determine if conditions existed where it was more effective to choose not to flock.

The first experiment showed that when the flock turns frequently (more than once every half mile), attempting to take advantage of wake vortices does more harm than good. For intermediate values, with turns more frequent than every 2.5 miles, smaller flocks were more efficient, while larger flocks were more effective when turns were less frequent. Next, two separate mock missions were conducted at various airspeeds to determine effectiveness of the flocking algorithm. The flock outperformed non-flocking aircraft at all conditions, but by a wider margin when operating at slower airspeeds. Best range airspeeds and best endurance airspeeds were slightly slower for a flock than for an individual aircraft. Overall, a flock of 10 aircraft in the first scenario was able to decrease fuel consumption by 14.2%, which enabled a 14.5% increase in endurance.

In the second scenario, a flock of 5 aircraft decreased fuel consumption by 7.3%, leading to an 8.1% increase in area covered. The smaller increase in performance is partially because the flock was smaller and also because the second scenario favored best range airspeed rather than best endurance airspeed, where flocking has a higher benefit margin. Overall, maximum range is shown in Figure 27 and **Error! Reference source not found.** to continually increase as more aircraft are added to the flock, though a principle of diminishing returns applies: the increase in range as the flock grows from one to three aircraft is nearly double the increase in range as the flock grows from three to fifteen aircraft.

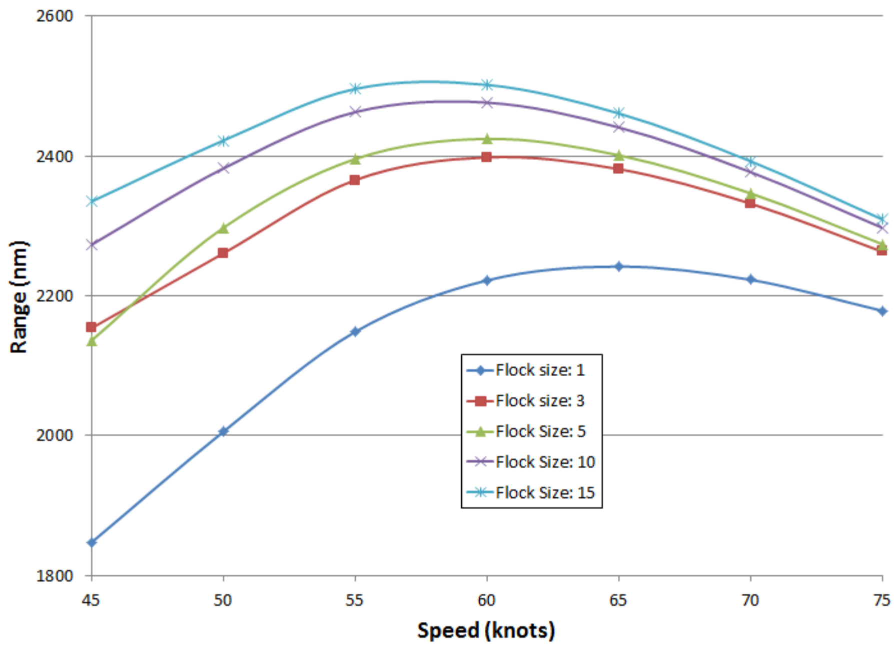


Figure 27: Maximum Flock Range

Table 6: Maximum Flock Range Increase with Flock Size

Flock Size	Range (nm)	Range Increase
1	2242	N/A
3	2398	7.0%
5	2425	8.1%
10	2477	10.5%
15	2502	11.6%

Although maximum range increases as aircraft are added, the maximum range airspeed decreases as the flock grows because the formation drag reduction only influences the induced portion of total drag, which is a larger at slower airspeeds.

V. Conclusions and Recommendations

Chapter Overview

The simulation results indicate that the chosen flocking algorithm leads to a significant decrease in induced drag with corresponding increases in aircraft range and endurance. A minor compromise was required between maximum aerodynamic benefit and collision avoidance. An increase in longitudinal spacing greatly reduced collision potential while only reducing fuel savings marginally. At this further aft position, the flock demonstrated an ability to complete two mock missions with less fuel consumption than non-flocking aircraft. Suggestions for future research include implementing a vertical dimension, varying airspeed with phase of flight, and implementing intelligent position changes.

Conclusions of Research

Flocking operations present significant capabilities unavailable to individual aircraft, but existing flocking research fails to take advantage of formation drag reduction. By maintaining a precise position relative to other aircraft in the flock, aircraft are able to significantly reduce drag, thereby decreasing fuel consumption and increasing range and endurance. The most difficult aspect of formation drag reduction is attaining and maintaining the proper formation position, especially as formation size increases. This simulation uses a formation geometric center control methodology whereby all aircraft attempt to maintain a desired position relative to the geometric center of the formation rather than the preceding aircraft. This methodology eliminates most "accordion" instabilities, where a slight disturbance in the front aircraft is amplified as it moves backwards through the formation. Instead, the flock responds intelligently when one aircraft falls out of position and maneuvers as a group to help it regain its desired position. Two other processes are also used to guide the flock: one which guides the flock toward a desired waypoint and cruise speed, and another which deters potential collisions within the flock. Inputs from these three processes were combined to calculate an overall steering command for each aircraft during each time step. A variety of weights, dampers, and buffer zones were used to determine an acceptable compromise between station keeping, navigation, and collision avoidance. Ultimately, the flock was configured sufficiently to preserve the ability to rapidly react to potential collisions while not devolving into unstable oscillations after minor disturbances. While this iterative parameter selection is suitable for the current guidance methodology and airframe properties, the configuration optimization study would need to be repeated if significant changes to other flock parameters were implemented.

The chosen spacing for aircraft within the flock was 6.5 wingspans longitudinally and 0.95 wingspans laterally (wingtips slightly overlapping). This was slightly outboard and significantly aft of the region of maximum aerodynamic benefit shown in Table 1. However, this region presented an unacceptable number of collisions during simulation testing. The same research paper that provided Table 1 also showed that a large fraction of the maximum benefit could still be realized by moving the spacing back to 6.5 wingspans and slightly outboard (Vachon, et al. 2003, 14). This is consistent with the preponderance of research which showed that the position of maximum benefit is far more sensitive to lateral changes but very forgiving of longitudinal changes. Simulations showed that this new position drastically reduced aircraft collisions while still reaping substantial drag reduction benefits.

Utilizing formation drag reduction within a flock, aircraft were able to significantly decrease drag and fuel consumption while increasing range and endurance. During a mock mission scenario, a flock of 10 aircraft was able to maintain a position which decreased induced drag by about 25% and total drag by about 9%. When factoring in landing fuel reserves and transit to and from a target area, this increased endurance over the target (known as "play time" or "vul time" in the USAF) by 14%. Savings were generally higher when the distance between turns was increased, so the overall vul time benefit is expected to increase correspondingly as the orbit radius increases. Overall, maximum range continually increases as more aircraft are added to the flock, though a principle of diminishing returns applies.

Significance of Research

Each semi-autonomous aircraft in a flock is able to intelligently determine its flight path in a manner which reduces the overall drag of the flock. This enables the flock to fly missions with longer range and endurance or increased payload. By demonstrating a general control methodology based on Formation Geometric Center, the groundwork has been laid for experimentation using actual aircraft. While the simulation was conducted using an aerodynamic model of a specific aircraft, it is generally applicable to an aircraft which is able to analyze its own position and that of the rest of the flock with the requisite frequency and accuracy. By utilizing this control procedure, the capabilities of a flocking aircraft are increased dramatically.

Recommendations for Future Research

The first obstacle to implementation of this simulation is the need to add a third dimension. This is not assessed to be a very difficult proposition as the majority of maneuvering is still accomplished in the X and Y dimensions. In fact, it is expected that adding the third dimension will significantly improve the flock's performance. In the process of attaining formation position after each turn, some aircraft spent a substantial amount of time in the region of aerodynamic downdraft which decreases performance. By utilizing the third dimension, aircraft will be able to avoid the area of detriment vertically while transiting to their desired horizontal position. Also, the simulation showed that the region of peak aerodynamic benefit was unsuitable for flocking because of the increased likelihood of collisions. However, most collisions occurred during the process of regaining formation position after turns. By implementing a vertical deconfliction after passing turns until attaining position, spacing requirements could be reduced and fuel saving increased.

One weakness of the simulation is that the flock maintained the same target airspeed for the entire simulation. In the first mission scenario, it would be ideal to transit to the target area at 70 knots, orbit for 24 hours at 45 knots, and return to base at 60 knots. One additional benefit of orbiting at a slower airspeed is smaller turn radius and decreased acoustic signature to avoid detection by the target. By following this profile, additional fuel savings would be realized. Although not currently programmed into the simulation, the ability to dynamically change airspeeds dependent on phase of flight could be programmed in relatively simply.

Additionally, an improved model for fuel consumption could be implemented to improve accuracy of the data. This simulation assumed a linear relationship between thrust required and fuel consumed. While this is generally true for intermediate ranges of engine operation, it typically underestimates fuel consumption at both ends of the spectrum. Implementing a more accurate fuel-thrust relationship will improve overall accuracy of the simulation.

Overall range was determined in **Error! Reference source not found.** by the distance travelled when the first aircraft ran out of fuel. However, the flock does not intelligently interact to share the burden of being the lead aircraft appropriately. Instead, as detailed the Chapter III, the flock simply rotates positions if a certain amount of time passes without any turns (in this case, 240 seconds). This could possibly lead to unequal load sharing if turns are encountered in a manner that does facilitate equal distribution. Intelligent sharing of the burden of being the first aircraft would increase overall flock range by preventing the most fuel-critical aircraft from keeping the front position.

Summary

The integration of flocking with formation drag reduction has been proven as a realistic concept and warrants further investigation and implementation. By utilizing this concept, fuel savings of 14% have been demonstrated but this is far from a maximum value. Fuel savings can be increased both by adjusting configurations within the model or improving the model itself. The current model provides a feasible compromise between collision avoidance and drag reduction, but provides opportunities to adjust the model if the relative priority of these two objectives changes.

Appendix A

This table was used by the simulation to determine C_{DR} based on relative position of aircraft, measured in wingspans. Rows represent longitudinal spacing, rounded to the nearest 0.5 wingspans. Columns represent lateral spacing, rounded to the nearest 0.05 wingspans. Spacing greater than 1.5 wingspans laterally or 40 wingspans longitudinally are assumed to have C_{DR} = 1. Longitudinal spacing under 2.0 wingspans was not available due to the extreme risk of collision inherent to collecting data at that condition. Lower C_{DR}s are shown in green, higher C_{DR}s in red. Data for longitudinal spacings of 2, 3, 4.5 and 6.5 are from (Vachon, et al. 2003, 14, 17) and for longitudinal spacing of are from (Ning 2011, 12). All other values are linearly interpolated or extrapolated to complete the table.

	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75
2.0	2.242	2.150	2.058	1.966	1.874	1.782	1.690	1.598	1.506	1.414	1.321	1.231	1.276	1.053	0.860	0.741
2.5	2.232	2.141	2.049	1.958	1.866	1.775	1.683	1.592	1.500	1.409	1.316	1.227	1.205	1.027	0.852	0.737
3.0	2.222	2.131	2.040	1.949	1.858	1.767	1.676	1.585	1.494	1.403	**1.312**	**1.223**	**1.134**	**1.000**	**0.844**	**0.733**
3.5	2.212	2.121	2.031	1.940	1.850	1.760	1.669	1.579	1.488	1.398	1.307	1.219	1.062	0.973	0.836	0.728
4.0	2.201	2.111	2.022	1.932	1.842	1.752	1.662	1.573	1.483	1.393	1.303	1.215	0.991	0.947	0.828	0.724
4.5	2.191	2.102	2.012	1.923	1.834	1.745	1.655	1.566	1.477	1.388	1.298	1.210	**0.920**	**0.920**	**0.820**	**0.720**
5.0	2.181	2.092	2.003	1.915	1.826	1.737	1.649	1.560	1.471	1.383	1.293	1.206	0.919	0.919	0.819	0.717
5.5	2.170	2.082	1.994	1.906	1.818	1.730	1.642	1.553	1.465	1.377	1.289	1.202	0.919	0.917	0.819	0.715
6.0	2.160	2.072	1.985	1.897	1.810	1.722	1.635	1.547	1.460	1.372	1.284	1.198	0.918	0.916	0.818	0.712
6.5	2.150	2.063	1.976	1.889	1.802	1.715	1.628	1.541	1.454	1.367	1.279	1.194	0.917	0.914	0.817	**0.709**
7.0	2.139	2.053	1.967	1.880	1.794	1.707	1.621	1.534	1.448	1.362	1.275	1.190	0.916	0.913	0.816	0.710
7.5	2.129	2.043	1.957	1.872	1.786	1.700	1.614	1.528	1.442	1.356	1.270	1.186	0.916	0.912	0.816	0.710
8.0	2.119	2.034	1.948	1.863	1.778	1.692	1.607	1.522	1.436	1.351	1.265	1.182	0.915	0.910	0.815	0.711
8.5	2.109	2.024	1.939	1.854	1.770	1.685	1.600	1.515	1.431	1.346	1.261	1.178	0.914	0.909	0.814	0.711
9.0	2.098	2.014	1.930	1.846	1.762	1.677	1.593	1.509	1.425	1.341	1.256	1.173	0.914	0.907	0.814	0.712
9.5	2.088	2.004	1.921	1.837	1.754	1.670	1.586	1.503	1.419	1.336	1.251	1.169	0.913	0.906	0.813	0.712
10.0	2.078	1.995	1.912	1.829	1.745	1.662	1.579	1.496	1.413	1.330	1.247	1.165	0.912	0.905	0.812	0.713
10.5	2.067	1.985	1.902	1.820	1.737	1.655	1.572	1.490	1.408	1.325	1.242	1.161	0.912	0.903	0.812	0.713
11.0	2.057	1.975	1.893	1.811	1.729	1.647	1.566	1.484	1.402	1.320	1.237	1.157	0.911	0.902	0.811	0.714
11.5	2.047	1.965	1.884	1.803	1.721	1.640	1.559	1.477	1.396	1.315	1.233	1.153	0.910	0.900	0.810	0.714
12.0	2.036	1.956	1.875	1.794	1.713	1.633	1.552	1.471	1.390	1.309	1.228	1.149	0.909	0.899	0.809	0.714
12.5	2.026	1.946	1.866	1.786	1.705	1.625	1.545	1.465	1.384	1.304	1.224	1.145	0.909	0.897	0.809	0.715
13.0	2.016	1.936	1.857	1.777	1.697	1.618	1.538	1.458	1.379	1.299	1.219	1.141	0.908	0.896	0.808	0.715
13.5	2.006	1.926	1.847	1.768	1.689	1.610	1.531	1.452	1.373	1.294	1.214	1.137	0.907	0.895	0.807	0.716
14.0	1.995	1.917	1.838	1.760	1.681	1.603	1.524	1.446	1.367	1.289	1.210	1.132	0.907	0.893	0.807	0.716
14.5	1.985	1.907	1.829	1.751	1.673	1.595	1.517	1.439	1.361	1.283	1.205	1.128	0.906	0.892	0.806	0.717
15.0	1.975	1.897	1.820	1.742	1.665	1.588	1.510	1.433	1.356	1.278	1.200	1.124	0.905	0.890	0.805	0.717
15.5	1.964	1.888	1.811	1.734	1.657	1.580	1.503	1.427	1.350	1.273	1.196	1.120	0.905	0.889	0.805	0.718
16.0	1.954	1.878	1.802	1.725	1.649	1.573	1.496	1.420	1.344	1.268	1.191	1.116	0.904	0.888	0.804	0.718
16.5	1.944	1.868	1.792	1.717	1.641	1.565	1.490	1.414	1.338	1.263	1.186	1.112	0.903	0.886	0.803	0.719
17.0	1.933	1.858	1.783	1.708	1.633	1.558	1.483	1.408	1.332	1.257	1.182	1.108	0.902	0.885	0.802	0.719
17.5	1.923	1.849	1.774	1.699	1.625	1.550	1.476	1.401	1.327	1.252	1.177	1.104	0.902	0.883	0.802	0.719
18.0	1.913	1.839	1.765	1.691	1.617	1.543	1.469	1.395	1.321	1.247	1.172	1.100	0.901	0.882	0.801	0.720
18.5	1.903	1.829	1.756	1.682	1.609	1.535	1.462	1.388	1.315	1.242	1.168	1.095	0.900	0.881	0.800	0.720
19.0	1.892	1.819	1.747	1.674	1.601	1.528	1.455	1.382	1.309	1.236	1.163	1.091	0.900	0.879	0.800	0.721
19.5	1.882	1.810	1.737	1.665	1.593	1.520	1.448	1.376	1.303	1.231	1.159	1.087	0.899	0.878	0.799	0.721
20.0	1.872	1.800	1.728	1.656	1.585	1.513	1.441	1.369	1.298	1.226	1.154	1.083	0.898	0.876	0.798	0.722
20.5	1.861	1.790	1.719	1.648	1.577	1.505	1.434	1.363	1.292	1.221	1.149	1.079	0.897	0.875	0.797	0.722
21.0	1.851	1.780	1.710	1.639	1.569	1.498	1.427	1.357	1.286	1.216	1.145	1.075	0.897	0.874	0.797	0.723
21.5	1.841	1.771	1.701	1.631	1.561	1.491	1.420	1.350	1.280	1.210	1.140	1.071	0.896	0.872	0.796	0.723
22.0	1.830	1.761	1.692	1.622	1.553	1.483	1.414	1.344	1.275	1.205	1.135	1.067	0.895	0.871	0.795	0.724
22.5	1.820	1.751	1.682	1.613	1.544	1.476	1.407	1.338	1.269	1.200	1.131	1.063	0.895	0.869	0.795	0.724
23.0	1.810	1.742	1.673	1.605	1.536	1.468	1.400	1.331	1.263	1.195	1.126	1.058	0.894	0.868	0.794	0.725

23.5	1.800	1.732	1.664	1.596	1.528	1.461	1.393	1.325	1.257	1.189	1.121	1.054	0.893	0.866	0.793	0.725
24.0	1.789	1.722	1.655	1.588	1.520	1.453	1.386	1.319	1.251	1.184	1.117	1.050	0.893	0.865	0.793	0.725
24.5	1.779	1.712	1.646	1.579	1.512	1.446	1.379	1.312	1.246	1.179	1.112	1.046	0.892	0.864	0.792	0.726
25.0	1.769	1.703	1.636	1.570	1.504	1.438	1.372	1.306	1.240	1.174	1.107	1.042	0.891	0.862	0.791	0.726
25.5	1.758	1.693	1.627	1.562	1.496	1.431	1.365	1.300	1.234	1.169	1.103	1.038	0.890	0.861	0.790	0.727
26.0	1.748	1.683	1.618	1.553	1.488	1.423	1.358	1.293	1.228	1.163	1.098	1.034	0.890	0.859	0.790	0.727
26.5	1.738	1.673	1.609	1.545	1.480	1.416	1.351	1.287	1.223	1.158	1.094	1.030	0.889	0.858	0.789	0.728
27.0	1.728	1.664	1.600	1.536	1.472	1.408	1.344	1.281	1.217	1.153	1.089	1.026	0.888	0.857	0.788	0.728
27.5	1.717	1.654	1.591	1.527	1.464	1.401	1.338	1.274	1.211	1.148	1.084	1.022	0.888	0.855	0.788	0.729
28.0	1.707	1.644	1.581	1.519	1.456	1.393	1.331	1.268	1.205	1.142	1.080	1.017	0.887	0.854	0.787	0.729
28.5	1.697	1.634	1.572	1.510	1.448	1.386	1.324	1.262	1.199	1.137	1.075	1.013	0.886	0.852	0.786	0.730
29.0	1.686	1.625	1.563	1.502	1.440	1.378	1.317	1.255	1.194	1.132	1.070	1.009	0.885	0.851	0.785	0.730
29.5	1.676	1.615	1.554	1.493	1.432	1.371	1.310	1.249	1.188	1.127	1.066	1.005	0.885	0.850	0.785	0.730
30.0	1.666	1.605	1.545	1.484	1.424	1.363	1.303	1.243	1.182	1.122	1.061	1.001	0.884	0.848	0.784	0.731
30.5	1.655	1.596	1.536	1.476	1.416	1.356	1.296	1.236	1.176	1.116	1.056	0.997	0.883	0.847	0.783	0.731
31.0	1.645	1.586	1.526	1.467	1.408	1.348	1.289	1.230	1.170	1.111	1.052	0.993	0.883	0.845	0.783	0.732
31.5	1.635	1.576	1.517	1.459	1.400	1.341	1.282	1.223	1.165	1.106	1.047	0.989	0.882	0.844	0.782	0.732
32.0	1.625	1.566	1.508	1.450	1.392	1.334	1.275	1.217	1.159	1.101	1.042	0.985	0.881	0.843	0.781	0.733
32.5	1.614	1.557	1.499	1.441	1.384	1.326	1.268	1.211	1.153	1.096	1.038	0.980	0.881	0.841	0.781	0.733
33.0	1.604	1.547	1.490	1.433	1.376	1.319	1.262	1.204	1.147	1.090	1.033	0.976	0.880	0.840	0.780	0.734
33.5	1.594	1.537	1.481	1.424	1.368	1.311	1.255	1.198	1.142	1.085	1.028	0.972	0.879	0.838	0.779	0.734
34.0	1.583	1.527	1.471	1.416	1.360	1.304	1.248	1.192	1.136	1.080	1.024	0.968	0.878	0.837	0.778	0.735
34.5	1.573	1.518	1.462	1.407	1.352	1.296	1.241	1.185	1.130	1.075	1.019	0.964	0.878	0.835	0.778	0.735
35.0	1.563	1.508	1.453	1.398	1.343	1.289	1.234	1.179	1.124	1.069	1.015	0.960	0.877	0.834	0.777	0.735
35.5	1.552	1.498	1.444	1.390	1.335	1.281	1.227	1.173	1.118	1.064	1.010	0.956	0.876	0.833	0.776	0.736
36.0	1.542	1.488	1.435	1.381	1.327	1.274	1.220	1.166	1.113	1.059	1.005	0.952	0.876	0.831	0.776	0.736
36.5	1.532	1.479	1.426	1.372	1.319	1.266	1.213	1.160	1.107	1.054	1.001	0.948	0.875	0.830	0.775	0.737
37.0	1.522	1.469	1.416	1.364	1.311	1.259	1.206	1.154	1.101	1.049	0.996	0.944	0.874	0.828	0.774	0.737
37.5	1.511	1.459	1.407	1.355	1.303	1.251	1.199	1.147	1.095	1.043	0.991	0.939	0.874	0.827	0.774	0.738
38.0	1.501	1.450	1.398	1.347	1.295	1.244	1.192	1.141	1.090	1.038	0.987	0.935	0.873	0.826	0.773	0.738
38.5	1.491	1.440	1.389	1.338	1.287	1.236	1.185	1.135	1.084	1.033	0.982	0.931	0.872	0.824	0.772	0.739
39.0	1.480	1.430	1.380	1.329	1.279	1.229	1.179	1.128	1.078	1.028	0.977	0.927	0.871	0.823	0.771	0.739
39.5	1.470	1.420	1.371	1.321	1.271	1.221	1.172	1.122	1.072	1.022	0.973	0.923	0.871	0.821	0.771	0.740
40.0	1.460	1.411	1.361	1.312	1.263	1.214	1.165	1.116	1.066	1.017	0.968	0.919	**0.870**	**0.820**	**0.770**	**0.740**

	0.80	0.85	0.90	0.95	1.00	1.05	1.10	1.15	1.20	1.25	1.30	1.35	1.40	1.45	1.50
2.0	**0.600**	**0.600**	**0.600**	**0.622**	**0.667**	**0.711**	**0.756**	**0.800**	**0.822**	**0.844**	**0.867**	0.889	0.911	0.933	0.956
2.5	0.600	0.555	0.577	0.622	0.666	0.711	0.766	0.811	0.833	0.855	0.867	0.889	0.911	0.932	0.953
3.0	**0.599**	**0.510**	**0.555**	**0.621**	**0.666**	**0.710**	**0.777**	**0.822**	**0.844**	**0.866**	**0.866**	0.890	0.910	0.930	0.950
3.5	0.593	0.547	0.583	0.641	0.677	0.720	0.785	0.821	0.843	0.867	0.867	0.890	0.910	0.930	0.950
4.0	0.586	0.583	0.612	0.660	0.689	0.730	0.792	0.821	0.841	0.867	0.867	0.891	0.910	0.930	0.950
4.5	**0.580**	**0.620**	**0.640**	**0.680**	**0.700**	**0.740**	**0.800**	**0.820**	**0.840**	0.867	0.868	0.891	0.910	0.930	0.950
5.0	0.606	0.624	0.615	0.657	0.684	0.726	0.783	0.821	0.841	0.868	0.868	0.891	0.911	0.930	0.950
5.5	0.633	0.628	0.590	0.634	0.668	0.713	0.767	0.821	0.841	0.868	0.869	0.891	0.911	0.930	0.950
6.0	0.659	0.633	0.565	0.611	0.653	0.699	0.750	0.822	0.842	0.868	0.869	0.892	0.911	0.930	0.949
6.5	**0.685**	**0.637**	**0.540**	**0.588**	**0.637**	**0.685**	**0.734**	0.823	0.842	0.869	0.870	0.892	0.911	0.930	0.949
7.0	0.686	0.638	0.543	0.591	0.639	0.688	0.736	0.824	0.843	0.869	0.870	0.892	0.911	0.930	0.949
7.5	0.686	0.639	0.546	0.594	0.642	0.690	0.737	0.824	0.843	0.869	0.871	0.893	0.911	0.930	0.949
8.0	0.687	0.640	0.549	0.597	0.645	0.692	0.739	0.825	0.844	0.870	0.871	0.893	0.912	0.930	0.949
8.5	0.687	0.641	0.553	0.600	0.647	0.695	0.741	0.826	0.845	0.870	0.872	0.893	0.912	0.930	0.949
9.0	0.688	0.642	0.556	0.603	0.650	0.697	0.743	0.826	0.845	0.870	0.872	0.893	0.912	0.930	0.949
9.5	0.688	0.642	0.559	0.606	0.652	0.699	0.745	0.827	0.846	0.871	0.872	0.894	0.912	0.930	0.949
10.0	0.689	0.643	0.562	0.608	0.655	0.701	0.747	0.828	0.846	0.871	0.873	0.894	0.912	0.930	0.949
10.5	0.689	0.644	0.565	0.611	0.658	0.704	0.749	0.828	0.847	0.871	0.873	0.894	0.912	0.930	0.949
11.0	0.690	0.645	0.568	0.614	0.660	0.706	0.751	0.829	0.847	0.872	0.874	0.895	0.913	0.930	0.948
11.5	0.690	0.646	0.571	0.617	0.663	0.708	0.753	0.830	0.848	0.872	0.874	0.895	0.913	0.931	0.948
12.0	0.691	0.647	0.574	0.620	0.665	0.711	0.754	0.831	0.848	0.872	0.875	0.895	0.913	0.931	0.948
12.5	0.691	0.648	0.578	0.623	0.668	0.713	0.756	0.831	0.849	0.873	0.875	0.895	0.913	0.931	0.948
13.0	0.692	0.649	0.581	0.626	0.670	0.715	0.758	0.832	0.850	0.873	0.876	0.896	0.913	0.931	0.948
13.5	0.693	0.650	0.584	0.628	0.673	0.718	0.760	0.833	0.850	0.873	0.876	0.896	0.913	0.931	0.948
14.0	0.693	0.651	0.587	0.631	0.676	0.720	0.762	0.833	0.851	0.874	0.877	0.896	0.914	0.931	0.948
14.5	0.694	0.652	0.590	0.634	0.678	0.722	0.764	0.834	0.851	0.874	0.877	0.897	0.914	0.931	0.948
15.0	0.694	0.653	0.593	0.637	0.681	0.725	0.766	0.835	0.852	0.874	0.878	0.897	0.914	0.931	0.948
15.5	0.695	0.654	0.596	0.640	0.683	0.727	0.768	0.835	0.852	0.875	0.878	0.897	0.914	0.931	0.948
16.0	0.695	0.655	0.600	0.643	0.686	0.729	0.770	0.836	0.853	0.875	0.879	0.898	0.914	0.931	0.947
16.5	0.696	0.656	0.603	0.646	0.689	0.731	0.771	0.837	0.854	0.875	0.879	0.898	0.914	0.931	0.947
17.0	0.696	0.657	0.606	0.648	0.691	0.734	0.773	0.838	0.854	0.876	0.879	0.898	0.914	0.931	0.947
17.5	0.697	0.658	0.609	0.651	0.694	0.736	0.775	0.838	0.855	0.876	0.880	0.898	0.915	0.931	0.947
18.0	0.697	0.659	0.612	0.654	0.696	0.738	0.777	0.839	0.855	0.876	0.880	0.899	0.915	0.931	0.947
18.5	0.698	0.659	0.615	0.657	0.699	0.741	0.779	0.840	0.856	0.876	0.881	0.899	0.915	0.931	0.947
19.0	0.698	0.660	0.618	0.660	0.701	0.743	0.781	0.840	0.856	0.877	0.881	0.899	0.915	0.931	0.947
19.5	0.699	0.661	0.621	0.663	0.704	0.745	0.783	0.841	0.857	0.877	0.882	0.900	0.915	0.931	0.947
20.0	0.699	0.662	0.625	0.666	0.707	0.748	0.785	0.842	0.857	0.877	0.882	0.900	0.915	0.931	0.947
20.5	0.700	0.663	0.628	0.668	0.709	0.750	0.786	0.843	0.858	0.878	0.883	0.900	0.916	0.931	0.947
21.0	0.700	0.664	0.631	0.671	0.712	0.752	0.788	0.843	0.859	0.878	0.883	0.900	0.916	0.931	0.946
21.5	0.701	0.665	0.634	0.674	0.714	0.755	0.790	0.844	0.859	0.878	0.884	0.901	0.916	0.931	0.946
22.0	0.701	0.666	0.637	0.677	0.717	0.757	0.792	0.845	0.860	0.879	0.884	0.901	0.916	0.931	0.946
22.5	0.702	0.667	0.640	0.680	0.720	0.759	0.794	0.845	0.860	0.879	0.885	0.901	0.916	0.931	0.946
23.0	0.702	0.668	0.643	0.683	0.722	0.761	0.796	0.846	0.861	0.879	0.885	0.902	0.916	0.931	0.946
23.5	0.703	0.669	0.647	0.686	0.725	0.764	0.798	0.847	0.861	0.880	0.886	0.902	0.917	0.931	0.946
24.0	0.703	0.670	0.650	0.688	0.727	0.766	0.800	0.847	0.862	0.880	0.886	0.902	0.917	0.931	0.946
24.5	0.704	0.671	0.653	0.691	0.730	0.768	0.802	0.848	0.863	0.880	0.886	0.902	0.917	0.931	0.946
25.0	0.704	0.672	0.656	0.694	0.732	0.771	0.803	0.849	0.863	0.881	0.887	0.903	0.917	0.931	0.946
25.5	0.705	0.673	0.659	0.697	0.735	0.773	0.805	0.850	0.864	0.881	0.887	0.903	0.917	0.931	0.946
26.0	0.705	0.674	0.662	0.700	0.738	0.775	0.807	0.850	0.864	0.881	0.888	0.903	0.917	0.931	0.945

26.5	0.706	0.675	0.665	0.703	0.740	0.778	0.809	0.851	0.865	0.882	0.888	0.904	0.917	0.931	0.945
27.0	0.707	0.675	0.669	0.706	0.743	0.780	0.811	0.852	0.865	0.882	0.889	0.904	0.918	0.931	0.945
27.5	0.707	0.676	0.672	0.709	0.745	0.782	0.813	0.852	0.866	0.882	0.889	0.904	0.918	0.931	0.945
28.0	0.708	0.677	0.675	0.711	0.748	0.785	0.815	0.853	0.866	0.883	0.890	0.904	0.918	0.931	0.945
28.5	0.708	0.678	0.678	0.714	0.751	0.787	0.817	0.854	0.867	0.883	0.890	0.905	0.918	0.932	0.945
29.0	0.709	0.679	0.681	0.717	0.753	0.789	0.819	0.855	0.868	0.883	0.891	0.905	0.918	0.932	0.945
29.5	0.709	0.680	0.684	0.720	0.756	0.792	0.820	0.855	0.868	0.884	0.891	0.905	0.918	0.932	0.945
30.0	0.710	0.681	0.687	0.723	0.758	0.794	0.822	0.856	0.869	0.884	0.892	0.906	0.919	0.932	0.945
30.5	0.710	0.682	0.690	0.726	0.761	0.796	0.824	0.857	0.869	0.884	0.892	0.906	0.919	0.932	0.945
31.0	0.711	0.683	0.694	0.729	0.763	0.798	0.826	0.857	0.870	0.885	0.893	0.906	0.919	0.932	0.944
31.5	0.711	0.684	0.697	0.731	0.766	0.801	0.828	0.858	0.870	0.885	0.893	0.906	0.919	0.932	0.944
32.0	0.712	0.685	0.700	0.734	0.769	0.803	0.830	0.859	0.871	0.885	0.893	0.907	0.919	0.932	0.944
32.5	0.712	0.686	0.703	0.737	0.771	0.805	0.832	0.859	0.872	0.886	0.894	0.907	0.919	0.932	0.944
33.0	0.713	0.687	0.706	0.740	0.774	0.808	0.834	0.860	0.872	0.886	0.894	0.907	0.920	0.932	0.944
33.5	0.713	0.688	0.709	0.743	0.776	0.810	0.835	0.861	0.873	0.886	0.895	0.908	0.920	0.932	0.944
34.0	0.714	0.689	0.712	0.746	0.779	0.812	0.837	0.862	0.873	0.887	0.895	0.908	0.920	0.932	0.944
34.5	0.714	0.690	0.716	0.749	0.782	0.815	0.839	0.862	0.874	0.887	0.896	0.908	0.920	0.932	0.944
35.0	0.715	0.691	0.719	0.751	0.784	0.817	0.841	0.863	0.874	0.887	0.896	0.908	0.920	0.932	0.944
35.5	0.715	0.692	0.722	0.754	0.787	0.819	0.843	0.864	0.875	0.888	0.897	0.909	0.920	0.932	0.944
36.0	0.716	0.692	0.725	0.757	0.789	0.822	0.845	0.864	0.875	0.888	0.897	0.909	0.921	0.932	0.943
36.5	0.716	0.693	0.728	0.760	0.792	0.824	0.847	0.865	0.876	0.888	0.898	0.909	0.921	0.932	0.943
37.0	0.717	0.694	0.731	0.763	0.794	0.826	0.849	0.866	0.877	0.889	0.898	0.910	0.921	0.932	0.943
37.5	0.717	0.695	0.734	0.766	0.797	0.828	0.851	0.866	0.877	0.889	0.899	0.910	0.921	0.932	0.943
38.0	0.718	0.696	0.737	0.769	0.800	0.831	0.852	0.867	0.878	0.889	0.899	0.910	0.921	0.932	0.943
38.5	0.718	0.697	0.741	0.771	0.802	0.833	0.854	0.868	0.878	0.890	0.900	0.911	0.921	0.932	0.943
39.0	0.719	0.698	0.744	0.774	0.805	0.835	0.856	0.869	0.879	0.890	0.900	0.911	0.921	0.932	0.943
39.5	0.719	0.699	0.747	0.777	0.807	0.838	0.858	0.869	0.879	0.890	0.900	0.911	0.922	0.932	0.943
40.0	**0.720**	**0.700**	**0.750**	**0.780**	**0.810**	**0.840**	**0.860**	**0.870**	**0.880**	0.891	0.901	0.911	0.922	0.932	0.943

Appendix B

The following MATLAB code runs the simulation between random points spaced two miles apart for 10 minutes of simulation time for a flock of 5 aircraft. Comments (prefaced by a %) attempt to explain the code to a reader with a beginning level of programming experience. The table in function getCDR has been removed for redundancy and can be referenced in Appendix A.

```
% Main
% Runs one iteration of test.
% Colombi, Jan 2010
% Lambach, Jun 2013-Feb 2014

% Initialization of flock and Main variables
[configs, stats] = configuration();
simTime = 1;

% Create first target waypoint
temp = rand*2*pi;%prevents first point from being too close to origin
flightPlan = [cos(temp)*2 sin(temp)*2];
%Alternatively, create a flight plan in the format [x1 y1; x2 y2]
waypoint = 1;
configs.target = flightPlan(waypoint,:);

% Creation of first aircraft
Flock = addAircraft(configs,[]);

% Create display window
if configs.draw
    fh=figure('Position',[400 1 800 800]);
    configs.figure_handle=fh;
end

while ((simTime <= configs.sim_duration)&&(stats.minFuel > 0))
    % If flock is not fully created, consider adding another aircraft
    % every genInterval seconds
    if (length(Flock)<configs.Number &&
(simTime/configs.genInterval)>length(Flock))
        Flock = addAircraft(configs,Flock);
    end

    % Move flock forward 1 time step
    Flock = move(configs, Flock);

    % Calculate statistics
    stats = getStats(configs,Flock,stats);
    Flock = calcAero(configs.Aero,stats.CDR,Flock,configs.timeStep);

    % Draw aircraft and overlays statistics
    if configs.draw
        drawFlock(configs, Flock, stats, simTime);
```

```
    end

    % If waypoint is reached, move to next waypoint
    distToTarget = XYtoPolar(getAvgPosition(Flock) - configs.target);
    avgVel = getAvgVelocity(Flock);
    timeToTarget = distToTarget(1)/avgVel(1);

    if (timeToTarget*3600 < configs.timeStep)
        %if target is within 1 time step
        waypoint = waypoint + 1;
        numPoints = size(flightPlan);
        if (waypoint > numPoints(1))
            waypoint = 1;
            temp = rand*2*pi;% Pick a random direction
            % Create new steerpoint legLength nm away in temp direction
            flightPlan =
[flightPlan(numPoints(1),1)+cos(temp)*configs.legLength
flightPlan(numPoints(1),2)+sin(temp)*configs.legLength];
        end
        configs.target = flightPlan(waypoint,:);
        old_heading = getAvgVelocity(Flock);
        new_heading = XYtoPolar(configs.target -
getAvgPosition(Flock));
        delta_heading = min(abs(old_heading(2)-new_heading(2)),2*pi-
abs(old_heading(2)-new_heading(2)));
        %Clue to flock that turn has occured so they can reorder
        if delta_heading*180/pi > configs.minReorderAngle
            configs.timeSinceRotation = -configs.timeStep;%will be set
to zero a few lines down
        end
        configs.timeSinceTurn = -configs.timeStep;%will be set to zero
a few lines down
        stats.numTurns = stats.numTurns + 1;
        stats.allInPos = false;
    end

    %Increment sim_time
    simTime=simTime+configs.timeStep;
    configs.timeSinceTurn = configs.timeSinceTurn + configs.timeStep;
    configs.timeSinceRotation = configs.timeSinceRotation +
configs.timeStep;
end

fuelBurned = zeros(length(Flock),1);
for i = 1:length(Flock)
    fuelBurned(i) = configs.fuelCapacity - Flock(i).fuel;
end

%Store and display measures or performance
simTime = simTime - 1;% To correct numbers for cumulative averages
MOPs = zeros(11,1);

MOPs(1) = std(fuelBurned);
```

```
MOPs(2) = 100*stats.cumuIn/((simTime/configs.timeStep)*(configs.Number-
1));
MOPs(3) = stats.cumuDist/(simTime/configs.timeStep)*6076;
MOPs(4) = stats.Hits;
MOPs(5) = stats.NearMisses;
MOPs(6) = stats.cumuTimeToPos/(stats.numTurns+stats.allInPos);
MOPs(7) = stats.cumuCDR/(simTime/configs.timeStep);
MOPs(8) = stats.fuelSavings;
MOPs(9) = sum(stats.totalDist)/sum(fuelBurned);
MOPs(10) = simTime;
MOPs(11) = range(fuelBurned)/mean(fuelBurned)*100;

if configs.draw
    fprintf('Furn burn standard deviation: %g\n',MOPs(1));
    fprintf('Cumulative Time In Position : %g%%\n',MOPs(2));
    fprintf('Average Distance out of Position : %g feet\n',MOPs(3));
    fprintf('Total number of hits : %g\n',MOPs(4));
    fprintf('Total number of near misses : %g\n',MOPs(5));
    fprintf('Average time to reach position : %g seconds\n',MOPs(6));
    fprintf('Average Coefficient of Drag Reduction : %g\n',MOPs(7));
    fprintf('Cumulative Fuel Savings : %g%%\n',MOPs(8));
    fprintf('Specific Range : %g nm/kg (%g
mpg)\n',MOPs(9),MOPs(9)*3.4973);
    fprintf('Total time of simulation : %g seconds\n',MOPs(10));
    fprintf('Fuel burn variation: %g%%\n',MOPs(11));
end

-------------------------------------

function [configs, Stats] = configuration(weights)
% Initialize and configure flocking simulation. All adjustable
% configurations (damper amount, aerodynamic properties, etc) are
defined
% here.  Also, you can pass in a vector of weights for the 9 rules.
%else it will default to my weights

% Colombi, Jan 2010
% Lambach, Jun 2013-Feb 2014

if nargin ~= 1 %If no inputs, use all ones
    % Separation, Positioning, Flock Navigation
    RuleWeights=[1 1 1];
else
    RuleWeights=weights;
end

% Airframe-specific properties: Roughly based on AAI Corporation's
Aerosonde

    %Physical airframe properties
    WingSpan = 9.5/6076;     % Nautical miles
    WingArea = 0.55;         % Meters squared
    EmptyMass = 8.5;         % Kilograms
    FuelCapacity = 5;        % Kilograms
```

```
    Epsilon = .1592;         % Dimensionless wing efficiency property
    CD0 = .03;               % Parasite drag (drag at 0 airspeed).
Dimensionless
    BurnRate = .00928627;    % Kilograms per Newton*Hour
                             % An Aerosonde traveled 3270 kms in 26.75
                             % hrs burning 3.9 kgs of fuel.  At this
                             % speed (65 knots), my calculations show
                             % 15.7 N of thrust required.  3.9/(26.75*
                             % 15.7) (McGeer 1999, 22)

    % Velocity limits
    VelocityMax=80;          % Knots (nautical miles per hour)
    VelocityOptimum=55;      % Knots
    VelocityMin=45;          % Knots
    % Angular Velocity (Turn Rate) (6 degrees/sec = 360 turn in 60
seconds)
    % In aviation, the "standard rate turn" is 3 degrees per second
    TurnRateMax = 6*pi/180; % Radians per second

    % Acceleration limits
    AccelMax = 1;            % Knots per second
    DecelMax = -1;
    % Angular Acceleration (Roll Rate) - reflects that aircraft can't
    % instantaneously go from 6 degrees/sec left to 6 degrees/sec right
    AngAccelMax = 3*pi/180; % Radians per seconds squared
    % Therefore, it takes 4 seconds to go from full left to full turn

    % Global constants
    Gravity = 9.8;           % Meters per second squared
    AirDensity = 1.2682;     % Kilograms per meter cubed

    %All AERO units scaled to SI (meters/kg)
    Aero =
struct('EmptyMass',EmptyMass,'Wingspan',WingSpan*1852,'WingArea',WingAr
ea,'AirDensity',AirDensity,'Epsilon',Epsilon,'CD0',CD0,'Gravity',Gravit
y,'BurnRate',BurnRate);

%Flock/Simulation Global Properties.  Have fun playing around with
these!
    FlockSize = 5;           % Number of aircraft (eventually)
    draw = true;             % Whether or not to draw flock
    legLength = 2;           % Distance between generated waypoints
    Spacing = [6.5 .9] .* WingSpan; % [streamwise wingtip_spacing]
                                   % Also: [Longitudinal Lateral]
                                   % Commanded flock spacing to gain
                                   % benefit from wingtip vortices
    Stagger = true;   % Whether or not aircraft will "stagger" - those
                      % on right side of "V" move back 1/2 streamwise
                      % spacing to avoid conflict between #2 and #3
                      % aircraft.
    SimDuration= 10*60;% Maximum simulation time (seconds).
    TimeStep = 1;     % Timestep of simulation (sec).  Positive number
    genInterval = 1; % Positive numbers. Generate an aircraft at origin
                      % every genInterval secs until reaching size
```

```
    rotInterval= 240; % How often to rotate positions within the flock
                      % so that the same aircraft isn't bearing all the
                      % burden of being in front
    moveDamper = [2*WingSpan 0.45];% Distance inside which inputs are
                 % dampened to facilitate flock stabilization, and
                 % amount of dampening
    rule1Damper = [15, 1.5, 1]; % [X Y Z] Increases bug-out zone for
                                % collision prevention.  When aircraft
                                % heading differs from flock average heading
                                % by more than X degrees, radius of bug-out
                                % zone is multiplied by Y.  Z modulates
                                % responses for when other aircraft are
                                % closing from behind.  Collision avoidance
                                % is primarily the closing aircraft's
                                % responsibility
    rule2Damper = [35, .3]; % [X Y] Damper for rule2 which dampens
                             % input by Y when more than X degrees off
                             % desired heading
    rule3Damper = [30, .2]; % [X Y] Damper for rule3 which dampens
                             % input by Y when within X degrees of
                             % commanded heading
    sepMargin= .75;          % Percent of the desired separation inside
                             % which rule 1 becomes active
    lookAhead = [10 0; 2 6; 1 4; 0.5 2];% Parameters to control
                                        % lookAhead in rule2_stationKeeping
    randomness=[.5 .5*(pi/180)]; %randomness of movement [speed
direction]
    minReorderAngle = 10;    % Flock will not reorder itself for turns
less
                             % less than this number of degrees

% Minimum spacing requirements for rule1_separation
if Stagger % Minimum desired spacing, measured in wingspans
    % Smaller of separation between #1/#2 and separation between #2/#3
    min_separation =
min(sqrt(Spacing(1)^2+Spacing(2)^2),sqrt((2*Spacing(2))^2+(Spacing(1)/2
)^2));
else
    % Smaller of separation between #1/#2 and separation between #2/#3
    min_separation = min(sqrt(Spacing(1)^2+Spacing(2)^2),2*Spacing(2));
end
% Use 95% of desired spacing
min_separation = min_separation*sepMargin*6076; % Measured in ft

% Hit or near miss of other boids (ft)
Hit = max(min_separation*(.2/sepMargin),WingSpan*6076);      % 20% of
closest desired or 1 wingspan
NearMiss = max(min_separation*(.5/sepMargin),2*WingSpan*6076); % 50% of
closest desired or 2 wingspans

% Save all these parameters in a configs structure
configs =
struct('Number',FlockSize,'draw',draw,'genInterval',genInterval,
'legLength', legLength, 'timeStep',TimeStep, 'velocity_max',
VelocityMax, 'velocity_min', VelocityMin,
```

```
'velocity_opt',VelocityOptimum,'turn_limit',
TurnRateMax,'turn_accel_limit',AngAccelMax,'separation_size',min_separa
tion, 'randomness',
randomness,'wingSpan',WingSpan,'spacing',Spacing,'stagger',Stagger,
'sim_duration', SimDuration, 'RuleWeights', RuleWeights,
'figure_handle', 0, 'target',[0
0],'Hit',Hit,'NearMiss',NearMiss,'maxAccel',AccelMax,'maxDecel',DecelMa
x,
'fuelCapacity',FuelCapacity,'timeSinceTurn',0,'timeSinceRotation',0,'ro
tateInterval',rotInterval,'moveDamper',moveDamper,'rule1Damper',rule1Da
mper,'rule2Damper',rule2Damper,'rule3Damper',rule3Damper,'lookAhead',lo
okAhead,'minReorderAngle',minReorderAngle,'Aero',Aero);

% Create a structure for collecting stats on mission simulation
Stats=struct('Hits',0,'NearMisses',0','avgSpeed',0,'currentlyIn',0,'CDR
',1,'cumuIn',0,'cumuDist',0,'cumuTimeToPos',0,'cumuCDR',0,'numTurns',0,
'allInPos',false,'fuelSavings',0,'minFuel',FuelCapacity,'totalDist',zer
os(FlockSize,1));
end

------------------------------------

function [ Flock ] = addAircraft(configs,Flock)
% Add an aircraft to the flock at [0 0] with min velocity, east heading

% Colombi, Jan 2010
% Lambach, July 2013

Aircraft = struct('position',[0, 0], 'velocity',[0, 0],'velocityXY',[0,
0],'accel',[0
0],'color','b','distance_off',0,'order',0,'fuel',configs.fuelCapacity,'
noCDRfuel',configs.fuelCapacity);

Aircraft.velocity(1) = configs.velocity_min;
Aircraft.velocityXY = PolartoXY(Aircraft.velocity);
Aircraft.order = length(Flock)+1;
Flock = [Flock Aircraft];

end

------------------------------------

function [Flock] = move(configs, Flock)
% Move the flock.  Apply all 4 rules (weighted) and limit turns based
% on aerodynamic laws and airframe performance limits

% Lambach, Jun 2013

%Calculate average position and velocity
avgPos = getAvgPosition(Flock);
avgVel = getAvgVelocity(Flock);
goalVel = XYtoPolar(configs.target - avgPos);
N = length(Flock);
turn = zeros(N,2);
```

```
for j = 1:N %First, calculate the turns.  Then, apply the turns.
    % Process rules
    % Separation: collision avoidance
    a1 = rule1_separation(configs, j, Flock, avgVel(2));
    % Station keeping: positioning for taking advantage of vortices
    [a2,
Flock(j).distance_off]=rule2_stationKeeping(configs,Flock,j,avgPos,avgV
el,goalVel(2));
    % Flock nav: Move toward next waypoint and attain optimum velocity
    a3 = rule3_velocityMatch(configs, Flock(j), avgPos);
    % Re-ordering: Change position within flock after turns/rotation
    Flock(j).order =
rule4_assignOrder(configs,Flock,j,avgPos,goalVel(2));

    % Turn aircraft that are actively manuevering away from another to
yellow
    if a1 == 0
        Flock(j).color = 'b';
    else
        Flock(j).color = 'y';
    end

    % Apply Weights
    a1 = a1*configs.RuleWeights(1);
    a2 = a2*configs.RuleWeights(2);
    a3 = a3*configs.RuleWeights(3);

    % Sum the rules for target turn direction
    turn(j,:)=a1+a2+a3;

    % Dampen inputs when in position to minimize oscillations
    if Flock(j).distance_off < configs.moveDamper(1)
        turn(j,:) = turn(j,:)*configs.moveDamper(2);
    end
end

% Calculate noise for the entire time step.  This reflects that wind
% gusts, when in close formation, are typically experienced equally for
% the entire formation.
noise = (configs.randomness .* [2*rand-1 2*rand-1]) .*
configs.timeStep;

for j = 1:N % Apply the turns
    % Limit the turn rate/acceleration
    turn(j,:)= aircraft_limit_turn(configs, turn(j,:), Flock(j).accel);

    % Apply acceleration to determine new velocity
    Flock(j).velocity = Flock(j).velocity + (turn(j,:) .*
configs.timeStep);

    % Add noise in velocity
    Flock(j).velocity = Flock(j).velocity + noise;
```

```
    % Scale velocity to (-pi, pi) range
    Flock(j).velocity(2) = rem(Flock(j).velocity(2) + 3*pi,2*pi) - pi;

    % Check min and max speed
    if(Flock(j).velocity(1) > configs.velocity_max)
        Flock(j).velocity(1) = configs.velocity_max;
    elseif(Flock(j).velocity(1) < configs.velocity_min)
        Flock(j).velocity(1) = configs.velocity_min;
    end

    % Save current velocity and acceleration
    Flock(j).velocityXY = PolartoXY(Flock(j).velocity);
    Flock(j).accel = turn(j,:);

    % Move to next position, based on time_step
    Flock(j).position = Flock(j).position +
(Flock(j).velocityXY.*configs.timeStep/3600);

end
end

-------------------------------------

function [ a1 ] = rule1_separation(configs, j, Flock, avgDirection )
% Rule 1 Prevent collisions.  Each aircraft has a "bug-out" buffer zone
% of a pre-defined radius that surrounds it. Also, if the aircraft is
% actively maneuvering (current heading differs from flock average
% heading by a pre-defined margin) it enlarges the buffer zone.
% Aircraft interrogates each of the other aircraft to determine if any
% are in this zone.  If so, aircraft calculates where each aircraft
% will be 1 second from now, using current velocity. If separation is
% projected to decrease, aircraft actively moves to avoid intruder.
% Aircraft initiates a turn away from the intruder, and either slows
% down or speeds up depending on whether the intruder was ahead of or
% behind it, respectively.  Finally, commanded turn is scaled according
% to the inverse square of proximity - if the intruder is on the edge.
% of the buffer zone, the response is not scaled. As the intruder moves
% closer, the response increases exponentially

% Lambach, Jun 2013

N = length(Flock);
turn = [0 0];
a1 = [0 0];
sep_allowed = configs.separation_size/6076;


% If more than "damper(1)" degrees from average heading, increase
% radius of bug-out zone
damper = configs.rule1Damper;
if (abs(Flock(j).velocity(2)-avgDirection) > damper(1)*pi/180) &&
(abs(Flock(j).velocity(2)-avgDirection) < (360-damper(1))*pi/180) ;
```

```
   sep_allowed = damper(2)*sep_allowed;
end

%Current position
xj = Flock(j).position(1);
yj = Flock(j).position(2);
%Projected position 1 second from now
xjnext = xj + Flock(j).velocityXY(1)/3600;
yjnext = yj + Flock(j).velocityXY(2)/3600;
for i = 1:N
   if (i ~= j)
       xi=Flock(i).position(1);
       yi=Flock(i).position(2);
       separation = sqrt((xj-xi)^2+(yj-yi)^2);
       if separation < sep_allowed; %Within my bug-out zone!
           xinext = xi + Flock(i).velocityXY(1)/3600;
           yinext = yi + Flock(i).velocityXY(2)/3600;
           separation_next = sqrt((xjnext-xinext)^2+(yjnext-yinext)^2);
           if separation_next < separation %Moving closer - take
evasive action!
               %Turn away from intruder
               turn(2)=atan2(yj-yi,xj-xi)-Flock(j).velocity(2);
               %Scale to (-pi, pi)
               turn(2)=rem(turn(2)+3*pi,2*pi)-pi;

               % If in front of you, slow down.  If behind, speed up
               if abs(turn(2)) < pi/2 %intuder is behind you
                   turn(1) = (configs.velocity_max -
Flock(j).velocity(1))*damper(3);
                   %scaled to prevent over-reactions
               else%intruder in front of you, slow down
                   turn(1) = configs.velocity_min -
Flock(j).velocity(1);
               end

               % Scale according to proximity.  If right at boundary
               % zone, scaled to 1.  As getting closer, increase scale
               a1 = a1 + turn .*
((configs.separation_size/separation)^2);
           end
       end
   end
end
end

-------------------------------------

function [ a2, dist_off ] = rule2_stationKeeping(configs, Flock, i,
avgPos, avgVel, goalHeading )
% Rule 2: This rule pulls aircraft to a user-specified position
% relative to formation geometric center.

% Lambach, Jun 2013
```

```
% Unit distance for appropriate offset from formation geometric center
offsetXY = offset_calc(length(Flock),Flock(i).order,configs.stagger);

% Convert unit distance to nautical miles (nm), adjusted for wingspan
offsetXY = offsetXY .* configs.spacing;

% Convert desired offset from cartesian to polar for orientation
offset = XYtoPolar(offsetXY);

% Orient by rotating desired offset to flock's desired velocity
offset(2) = offset(2) + goalHeading;

% Converted oriented offset back to cartesian for translation
offsetXY = PolartoXY(offset);

% Apply offset to current flock Flock Geometric Center (FGC)
desired_position = avgPos + offsetXY;

% Calculate how far aircraft currently is from desired position
dist_off = sqrt(sum((desired_position - Flock(i).position).^2));

%Looks ahead a defined number of seconds, calculates the desired
% position in that time (assuming Flock continues at current speed and
% goal direction). As aircraft gets closer to desired position, no need
% to look ahead as far.  This expedites the final join-up
look_ahead = configs.lookAhead(1);
% # of secs to look ahead, depends on proximity to desired position
if dist_off < configs.wingSpan*configs.lookAhead(2,1)
    look_ahead = configs.lookAhead(2,2);
elseif dist_off < configs.wingSpan*configs.lookAhead(3,1)
    look_ahead = configs.lookAhead(3,2);
elseif dist_off < configs.wingSpan*configs.lookAhead(4,1)
    look_ahead = configs.lookAhead(4,2);
end

look_ahead_position = desired_position + [avgVel(1)*cos(goalHeading)
avgVel(1)*sin(goalHeading)] .* (look_ahead/3600);
desired_velocity = XYtoPolar((look_ahead_position - Flock(i).position)
./ (look_ahead/3600));

%Determine required turn from Current Velocity to Desired Velocity
%Left = positive, right = negative.  Scaled to (-pi, pi) range
desired_turn = rem(desired_velocity(2) - Flock(i).velocity(2) +
3*pi,2*pi)-pi;

if  abs(desired_turn) > 3*pi/4  %4.5 to 7.5 o'clock position
    % Desired position is behind you.  Just slow down, don't turn,
    % allow FGC to catch up
    a2 = [(configs.velocity_min - Flock(i).velocity(1)) 0];
elseif abs(desired_turn) > pi/4%1.5 to 4.5 and 7.5 to 10.5 o'clock
position
    % Desired position is slightly behind and to the left/right. Slow
    % and initiate a slight turn. This turn should quickly move you
```

```
    % into the below category
    a2 = [configs.velocity_min - Flock(i).velocity(1) desired_turn];
else %10.5 to 1.5 o'clock position
    %Desired position is within the front 180 degree field of view.
    %Turn toward target and accelerate (or slow) to target velocity
    a2 = [desired_velocity(1) - Flock(i).velocity(1) desired_turn];
end

%If going more than 90 degrees from goal direction (usually right after
%flock generation or turns), dampen the input for this rule to avoid
%circling difficulties during joinup.  This rule makes sure the entire
%flock turns the same direction for large turns (particularly over 160
%degrees), which prevents high collision-potential situations.

if abs(Flock(i).velocity(2) - goalHeading) >
configs.rule2Damper(1)*pi/180
    a2 = a2 .* configs.rule2Damper(2);
end

end

-------------------------------------

function [ offset ] = offset_calc( N, i, stagger )
    % Calculates desired number of units offset given flock of size N
    % and aircraft position i.  Returns desired offset [x y]

    if rem(N,2) == 1; %Odd number of aircraft
        offset(1) = (floor(N/2)+1)*floor(N/2)/N - floor(i/2);
        offset(2) = floor(i/2)*(rem(i,2)-.5)*-2;
    else %Even number of aircraft
        offset(1) = N/4 - floor(i/2);
        offset(2) = floor(i/2)*(rem(i,2)-.5)*-2 -.5;
    end

    if stagger% moves all acft on right side of "v" back an extra 1/2
              % unit to prevent wingtip conflicts between #2/#3.
        if i ~= 1
           offset(1) = (N+2)*(N-1)/(4*N) - i/2;
        else
           offset(1) = (N+2)*(N-1)/(4*N);
        end
    end
end

-------------------------------------

function [a3]=rule3_velocityMatch(configs, Aircraft, avgPosition)
% Rule 3: Move the entire flock toward the target waypoint and
% accel/decel toward optimum velocity.  Also, features damper so that
% this rule will not overpower rule2 when aircraft are close enough to
% the desired heading. Finally, causes aircraft to decelerate when more
% than 90 degrees from desired heading (no sense accelerating if you're
% going the wrong way!)
```

```
%June 2013 Lambach

%Global direction required to reach target
vector_to_target = XYtoPolar(configs.target - avgPosition);
desired_turn = (vector_to_target(2) - Aircraft.velocity(2));

%correct to proper (-pi, pi) range
a3(2) = rem(desired_turn+3*pi,2*pi)-pi;

if abs(desired_turn) < configs.rule3Damper(1)*pi/180
% If turns is less than amount of degrees defined in configs, dampens
% turn input from this rule. This allows rule2 to overpower rule3 once
% aircraft are moving in the generally correct diretion
    a3(2) = a3(2)*configs.rule3Damper(2);
end

%If pointed away from target, slow down.  If pointed toward target,
%accel/decel toward optimum cruise speed
if abs(a3(2)) > 90 * pi/180
    a3(1) = configs.velocity_min - Aircraft.velocity(1);
elseif ((Aircraft.velocity(1) > configs.velocity_opt + configs.maxDecel
) && (Aircraft.velocity(1) < configs.velocity_opt + configs.maxAccel))
    %Dampen to prevent jumping around desired velocty
    a3(1) = (configs.velocity_opt - Aircraft.velocity(1))/2;
elseif Aircraft.velocity(1) < configs.velocity_opt
    a3(1) = configs.maxAccel;
else
    a3(1) = configs.maxDecel;
end
end

-------------------------------------

function [ order ] = rule4_assignOrder(configs,Flock,j,avgPos,goalDir)
% Each aircraft assesses whether it is necessary to change its position
% within the formation and if so, decides to move to. Aircraft need to
% reorder if either: just passed a turnpoint, or haven't reordered in
% configs.reorderInterval seconds.  If after a turn, Aircraft
% determines its position relative to the flock centerpoint and
% relative direction of travel and assumes appropriate position.  If
% after the specified interval, aircraft rotate one position clockwise
% Lambach, Jun 2013

order = Flock(j).order;
N = length(Flock);

if(N<2) %No need to calculate if there is only 1 aircraft in the
formation
    return;
end

if configs.timeSinceRotation == 0 %Flock just turned, time to reorder!
```

```
    %Determine angular offset from each aircraft with respect to
desired velocity
    aircraftPosition = zeros(N,1);
    for i = 1:N
        temp = XYtoPolar(Flock(i).position - avgPos);
        %Scale to (0,2*pi) range
        aircraftPosition(i) = rem(temp(2) - goalDir+4*pi,2*pi);
    end

    %Determine how many have a higher angular difference
    numberLower = 0;
    for i = 1:N
        if aircraftPosition(i) < aircraftPosition(j)
            numberLower = numberLower + 1;
        elseif (aircraftPosition(i) == aircraftPosition(j)) && (i < j)
            %Prevents ties: tie goes to aircraft with lower original
position
            numberLower = numberLower + 1;
        end
    end

    %   This section determines what position for the aircraft to go
    %   to, from the perspective of the center of the flock, rotating
    %   clockwise, starting in the direction of the flock's desired
    %   velocity. The first seen will be "1", then "3", then "5", and
    %   so on until the largest odd number.  From here, they will count
    %   down from the largest even number, ending with "4" and then "2"
    if numberLower == 0
        order = 1;
    elseif numberLower <= N/2 % on the left half of the formation
        order = numberLower*2;
    else %on the right half of the formation
        order = (N-numberLower)*2 + 1;
    end

elseif rem(configs.timeSinceRotation,configs.rotateInterval) == 0 %Time
to rotate
    if rem(order,2) == 1 %Odd-ordered aircraft slide back
        order = order + 2;
        if order > N %except last one: move to end of left side
            if rem(N,2) == 1%even-sized flock
                order = order - 3;
            else %odd-sized flock
                order = order - 1;
            end
        end
    else %Even-ordered aircraft slide forward
        order = order - 2;
        if order == 0 %except #2 moves to #1 position
            order = 1;
        end
    end
end
end
```

```
------------------------------------

function [turn] = aircraft_limit_turn(configs, turn, accel)
% Limit the Aircraft change of direction, given a proposed turn and
% acceleration. Based on aircraft performance properties defined in
configs

    % Turn rate limit
    % Related to max bank angle/'g' limits
    if (abs(turn(2)) > configs.turn_limit )
        % Limit to maximum turn rate
        if turn(2) > 0
            turn(2) = configs.turn_limit;
        else
            turn(2) = -configs.turn_limit;
        end
    end

    % Angular acceleration limit
    % Related to roll rate/aileron deflection.  Turn rate cannot change
    % too much from last iteration
    if ( turn(2) > accel(2) + configs.turn_accel_limit)
        turn(2) = accel(2) + configs.turn_accel_limit;
    elseif ( turn(2) < accel(2) - configs.turn_accel_limit )
        turn(2) = accel(2) - configs.turn_accel_limit;
    end

    % Linear acceleration limit
    if (turn(1) > configs.maxAccel)
        turn(1) = configs.maxAccel;
    elseif (turn(1) < configs.maxDecel)
        turn(1) = configs.maxDecel;
    end
end

------------------------------------

function [stats] = getStats(configs, Flock, stats)
% Calculates all statistics/measures of performance of the flock during
% every time interval

% Colombi, Jan 2010...Sept 2010
% Lambach, July 2013

N=length(Flock);
stats.currentlyIn = 0;


for i = 1:N
    for j = i+1:N
        d=sqrt(sum((Flock(i).position - Flock(j).position).^2));
```

```
        % Did any of the aircraft hit each other?
        if (d < configs.Hit/6076)
            stats.Hits=stats.Hits + 1;
            if configs.draw
                fprintf('Bird %d hit Bird %d: %g ft\n', i, j, d*6076);
            end

        % Are any of the aircraft too close>
        elseif (d < configs.NearMiss/6076)
            stats.NearMisses=stats.NearMisses + 1;
            if configs.draw
                fprintf('Bird %d nearmiss Bird %d: %g ft\n', i, j,
d*6076);
            end
        end
    end

    %Check if aerodynamic benefit is achieved
    stats.CDR(i) = 1;
    for j=1:N
        if i ~= j
            benefit =
getBenefit(Flock(i),Flock(j),configs.wingSpan,configs.spacing);
            % If "In" position, increment stats.currentlyIn
            stats.currentlyIn = stats.currentlyIn + benefit(1);
            stats.CDR(i) = stats.CDR(i) * benefit(2);
        end
    end
end

% Check if all birds just reached position.  If so, update stats
if ( (stats.allInPos == false) && (stats.currentlyIn == N-1) && (N ~=
1) )
    stats.allInPos = true;
    stats.cumuTimeToPos = stats.cumuTimeToPos + configs.timeSinceTurn;
end

%Check fuel consumption with benefit of Drag Reduction, compare to fuel
%consumption when ignoring Drag Reduction
optFuel = [0 0];
nonOptFuel = [0 0];
for i = 1:N
   optFuel = optFuel + Flock(i).fuel;
   nonOptFuel = nonOptFuel + Flock(i).noCDRfuel;
   stats.minFuel = min(stats.minFuel, Flock(i).fuel);
end
optFuel = optFuel/N;
nonOptFuel = nonOptFuel/N;
if (configs.fuelCapacity-nonOptFuel ~= 0)
    stats.fuelSavings = (optFuel-nonOptFuel)/(configs.fuelCapacity-
nonOptFuel)*100;
end

% Calculate average speed, distance from target position, and total
```

```
% distance traveled
stats.distance_off = 0;
stats.avgSpeed = 0;
for i = 1:N
    stats.avgSpeed = stats.avgSpeed + Flock(i).velocity(1);
    stats.distance_off = stats.distance_off + Flock(i).distance_off;
    stats.totalDist(i) = stats.totalDist(i) +
Flock(i).velocity(1)*configs.timeStep/3600;
end
stats.avgSpeed = stats.avgSpeed/N;
stats.distance_off = stats.distance_off/N;

% Keep track of cumulative stats
stats.cumuIn = stats.cumuIn + stats.currentlyIn;
stats.cumuDist = stats.cumuDist + stats.distance_off;
if N > 1
    stats.cumuCDR = stats.cumuCDR + (sum(stats.CDR)-1)/(N-1);
else
    stats.cumuCDR = stats.cumuCDR + 1;
end

end
```

```
function [ benefit ] = getBenefit( Aircraft1, Aircraft2, wingspan,
spacing)
%getBenefit Returns aerodynamic benefit from Aircraft1 to Aircraft2
%   Determines position of Aircraft2 relative to Aircraft1's current
%   position and velocity.  Checks if current position lies within the
%   pre-defined benefit map and returns the benefit.

benefit = [false 1];
%benefit(1) is whether the aircraft is within 10% of the commanded
% position benefit(2) is the coefficient of drag reduction caused by
% the relative position

%Position of Aircraft2 relative to Aicraft1 - in polar
relativePosition = XYtoPolar(Aircraft2.position - Aircraft1.position);

%Rotate relative to Aircraft1's velocity and back to cartesian
relativePosition(2) = relativePosition(2) - Aircraft1.velocity(2);
relativePosition = PolartoXY(relativePosition);

if
(abs(relativePosition(2))<spacing(2)*1.1)&&(abs(relativePosition(2))>sp
acing(2)*.9)
%If lateral position within 10% of commandeded position
    if (-relativePosition(1)<spacing(1)*1.6)&&(-
relativePosition(1)>spacing(1)*.9)
%If longitudinal position is between 10% too close and 60% too far.
% This takes into account that when 'stagger' is enabled, the #3
% aircraft will trail the #1 aircraft byan extra 50%
        benefit(1) = true;
```

```
    end
end

%Convert to unit length by accounting for wingspan
relativePosition = relativePosition ./ wingspan;
if ( abs(relativePosition(2)) < 1.5 )
%Aicraft that are separated more than 1.5 wingspans laterally receive
%negligible benefit
    if ((relativePosition(1) > 2) && (relativePosition(1)<40))
%No data was available for aircraft with less than 2 wingspans
% longitudinal Spacing, and this position will lead to a 'hit' in this
% simulation, so no benefit is given.  Also, research shows that at
% longitudinal position greater than about 40 wingspans, the wake
% vortex locations become unpredictable and benefits are marginal
       benefit(2) = getCDR(round(relativePosition(1)*2-
3),round(abs(relativePosition(2))*20+1));
       %Conversions explained in getCDR function
    end
end

end

-------------------------------------

function [CDR] = getCDR(R,C)
%Table representing the relative induced drag caused by maintaining a
%certain position relative to another aircraft.  Rows represent
%longitudinal position from 2 to 40 wingspans in trail, with .5
% wingspan increment. Columns represent lateral position from 0
%(directly in trail) to 1.5 (half wingspan gap) scaled every .05.

%Lookup values in table use formula Table(Y*2-3, abs(X*20)+1), so if
%one aircraft is trailing another aircraft by 5 wingspans (Y=5) and
%wingtips overlapping 10% (X=.9), lookup Table(7,19)

%Lambach 2014

CDR_Table = [REMOVED - See Appendix A]
CDR = CDR_Table(R,C);
end

-------------------------------------

function [ Flock ] = calcAero(Aero, CDR, Flock, timeStep)
% Calculates current aerodynamic properties for flock and decrements
fuel

% Lambach, Jan 2014

N = length(Flock);

for i = 1:N
% Convert velocity from knots to meters per second
```

```
velocity = Flock(i).velocity(1)*463/900;
% Convert acceleration from knots per second to meters per second
squared
accel = Flock(i).accel(1)*463/900;

% Calculate bank angle
theta = atan((Flock(i).accel(2)*velocity)/(Aero.Gravity));

% Calculations using Coefficient of Drag Reduction, based on wingtip
% vortex Coefficient of lift: 2*m*g/(pho*V^2*S*cos(theta)).  All units
% SI (m/kg/s)
CL =
(2*(Flock(i).fuel+Aero.EmptyMass)*Aero.Gravity)/(Aero.AirDensity*veloci
ty^2*Aero.WingArea*cos(theta));
% Coefficient of drag: Parasite drag (CD0) + Induced drag*CDR
CD = Aero.CD0 +
(CL^2*Aero.WingArea*CDR(i))/(pi*Aero.Wingspan^2*Aero.Epsilon);
% Thrust required to achieve desired acceleration with current mass,
% velocity and Coefficient of Drag - measured in Newtons
thrust = ((Flock(i).fuel+Aero.EmptyMass)*(accel))+
(Aero.AirDensity*velocity^2*Aero.WingArea*CD)/2;
%Fuel required to achieve required thrust
fuel = thrust * Aero.BurnRate * (timeStep/3600);
Flock(i).fuel = Flock(i).fuel - max(fuel,0);% Decrement fuel

% Calculations without benefit of CDR (pretend it doesn't exist)
% Coefficient of lift: 2*m*g/(pho*V^2*S*cos(theta)).  All units SI
(m/kg/s)
CL =
(2*(Flock(i).noCDRfuel+Aero.EmptyMass)*Aero.Gravity)/(Aero.AirDensity*(
velocity)^2*Aero.WingArea*cos(theta));
% Coefficient of drag: Parasite drag (CD0) + Induced drag
CD = Aero.CD0 + (CL^2*Aero.WingArea)/(pi*Aero.Wingspan^2*Aero.Epsilon);
% Thrust required to achieve desired acceleration with current mass,
% velocity and Coefficient of Drag - measured in Newtons
thrust = ((Flock(i).noCDRfuel+Aero.EmptyMass)*(accel))+
(Aero.AirDensity*(velocity)^2*Aero.WingArea*CD)/2;
%Fuel required to achieve required thrust
fuel = thrust * Aero.BurnRate * (timeStep/3600);
Flock(i).noCDRfuel = Flock(i).noCDRfuel - max(fuel,0);% Decrement fuel

% Paint birds according to CDR
if Flock(i).color == 'y'
    % Do nothing - aircraft was already painted yellow for other
reasons
elseif CDR(i) < .75
    Flock(i).color = 'g'; % Green = good
elseif CDR(i) > 1.05
    Flock(i).color = 'r'; % Red = bad
end

end
end
```

```
function [] = drawFlock(configs, Flock, stats, simTime)
% Draws the flock.  Also, calculates how spread out the flock is from
% the flock centerpoint to determine an appropriate range to zoom the
% screen. Also overlays calculated statistics for real-time
% visualization.

% Colombi, Jan 2010
% Lambach, July 2013

N = length(Flock);

% Determine new range to zoom in
flockCenter = getAvgPosition(Flock);
spread = zeros(N,2);

target=configs.target;

figure(configs.figure_handle);
hold off;
plot(0,0,'rs')
hold on;


for i = 1:N
    % Draw the aircraft as a triangle
    triangleAircraft(Flock(i), configs.wingSpan);

    % Determine how far the aircraft is from the flock centerpoint
    spread(i,:)=flockCenter - Flock(i).position;
end

% Find the max spread
gridSize = max(max(abs(spread)))+ configs.wingSpan*20;
zoomBound = [flockCenter(1)-gridSize flockCenter(1)+gridSize
flockCenter(2)-gridSize flockCenter(2)+gridSize];

ch=get(configs.figure_handle,'Children');
axis(zoomBound);
set(ch,'XTick',-100:100);
set(ch,'YTick',-100:100); grid on;

% Move location where target is drawn to boundary, unless it is already
% within boundary
radius = configs.wingSpan*5;
if max(abs(target-flockCenter))>(gridSize)
    relativeLoc = target - flockCenter;

    % Move to boundary
    relativeLoc = relativeLoc .* (gridSize/max(abs(relativeLoc)));
    target = flockCenter + relativeLoc;
end
```

```
% Green star showing location of flock centerpoint
plot(flockCenter(1),flockCenter(2),'g*');

% Green star and red circle showing location of target waypoint
plot(target(1), target(2), 'g*');
targetCircle=zeros(127,2);
for i = -3.15:.05:3.15
    targetCircle(round(i*20+64),:)=[target(1)+2*radius*cos(i)
target(2)+2*radius*sin(i)];
end
plot(targetCircle(:,1), targetCircle(:,2),'r-');

drawStats(configs, stats, zoomBound, simTime);

end
```

```
function  [] = triangleAircraft(Aircraft, L)
% Draws a triangle representing each aircraft, based on aircraft
% position, heading and color, size L

x=Aircraft.position(1);
y=Aircraft.position(2);
angle = Aircraft.velocity(2);
p1 =[x+(L/2)*cos(angle+pi/2) y+(L/2)*sin(angle+pi/2)];
p2 =[x+(L/2)*cos(angle-pi/2) y+(L/2)*sin(angle-pi/2)];
p3 =[x+(L)*cos(angle) y+(L)*sin(angle)] ;
T=[p1;p2;p3];
fill(T(:,1),T(:,2),Aircraft.color);

end
```

```
function [  ] = drawStats(configs, stats, zoomBound, time)
% Display statistics on graph of moving aircraft

% Colombi, Jan 2010
% Lambach, Jun 2013

c1=strcat('Time:',num2str(round(time)));
c2=strcat('Hits:',num2str(stats.Hits));
c3=strcat('Near misses:',num2str(stats.NearMisses));
c4=strcat('Avg speed:',num2str(stats.avgSpeed,'%.2f'));
c5=strcat('Boids In Position:',num2str(stats.currentlyIn));
c6=strcat('Cumulative time In position
:',num2str(100*stats.cumuIn/((time/configs.timeStep)*(configs.Number-
1)),'%.1f%%'));
c7=strcat('Cumulative avg distance Off
:',num2str(stats.cumuDist/(time/configs.timeStep)*6076,'%.1f'));
```

```
c8=strcat('Avg Coeff Drag Reduc:',num2str((sum(stats.CDR)-
1)/(length(stats.CDR)-1),'%.2f'));
c9=strcat('Cumulative fuel
savings:',num2str(mean(stats.fuelSavings),'%.2f%%'));
c10=strcat('Current avg distance
off:',num2str(stats.distance_off*6076,'%.2f'));
C={c1,c2,c3,c4,c5,c6,c7,c8,c9,c10};


text(zoomBound(1)*.95 +
zoomBound(2)*.05,zoomBound(4)*.95+zoomBound(3)*.05,char(C),'FontSize',6
,'BackgroundColor',[.7 .9
.7],'HorizontalAlignment','left','VerticalAlignment','top');

end

-------------------------------------

function [ XY ] = PolartoXY( Polar )
%PolartoXY Converts vector from Polar to Cartesian
%   Converts a vector from (distance, angle) to (x,y), with angle
measured
%   in radians counterclockwise from x-axis.
% Lambach June 2013

XY = [Polar(1)*cos(Polar(2)) Polar(1)*sin(Polar(2))];

end

-------------------------------------

function [ Polar ] = XYtoPolar( XY )
%XYtoPolar Converts vector from Cartesian to Polar
%   Converts a vector from (x, y) to (distance, angle), with angle
measured
%   in radians counterclockwise from x-axis.
% Lambach June 2013

Polar = [sqrt(XY(1)^2+XY(2)^2) atan2(XY(2),XY(1))];

end

-------------------------------------

function [ velocity ] = getAvgVelocity( Flock )
% Returns non-weighted average velocity in polar form (speed,direction)

N = length(Flock);
velocity = Flock(1).velocityXY;
for i=2:N
    velocity = velocity + Flock(i).velocityXY;
end
velocity = XYtoPolar(velocity/N);
```

```
end

-------------------------------------

function [ position ] = getAvgPosition( Flock )
%   Returns non-weighted average current position of the flock

N = length(Flock);
position = Flock(1).position;
for i=2:N
    position = position + Flock(i).position;
end
position = position/N;

end
```

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Vita

Captain Jacob L. Lambach graduated from Upper St. Clair High School in Pittsburgh, Pennsylvania. He entered undergraduate studies at the United States Air Force Academy in Colorado Springs, Colorado where he was a Distinguished Graduate with a Bachelor of Science degree in Mechanical Engineering in May 2008. He was also commissioned as a Second Lieutenant at the Air Force Academy and earned a slot in Undergraduate Pilot Training.

His first assignment was to Sheppard Air Force Base for Euro-NATO Joint Jet Pilot Training where he flew both the T-6 and T-38 trainer aircraft (and learned all the formations in Figure 1). After graduating in February 2010, he was selected to fly the KC-135R/T Stratotanker at Kadena Air Base, Japan, where he conducted air-to-air refueling, airlift, and aeromedical evacuation missions in the Pacific theater. While stationed at Kadena, he deployed twice to southwest Asia in support of Operations ENDURING FREEDOM and NEW DAWN, and was named 18th Operations Group Aircraft Commander of the Year in 2012.

In September 2013, he was reassigned to fly the MC-12W Liberty tactical reconnaissance aircraft stationed at Beale Air Force Base, California, which flies missions much like that shown in Figure 22, though with significantly less endurance. While busy as a mobility pilot, aircraft commander, readiness officer, executive officer, and mission commander from 2011 to 2014, Captain Lambach also entered the Graduate School of Engineering and Management, Air Force Institute of Technology via Distance

Learning. Upon graduation, he will deploy to Afghanistan in support of Operation ENDURING FREEDOM.

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14. ABSTRACT
Craig Reynolds, in the seminal research into simulated flocking, developed a methodology to guide a flock of birds using three rules: collision avoidance, flock centering, and velocity matching. By modifying these rules, a methodology was created so that each aircraft in a "flock" maintains a precise position relative to the preceding aircraft. By doing so, each aircraft experiences a decrease in induced aerodynamic drag and increase in fuel efficiency. Flocks of semi-autonomous aircraft present the warfighter with a wide array of capabilities for accomplishing missions more effectively. By introducing formation drag reduction, overall fuel consumption is reduced while range and endurance increase, expanding war planners' options. A simulation was constructed to determine the feasibility of the drag reduction flock in a two-dimensional environment using a drag benefit map constructed from existing research. Due to both agent interaction and wind gust variability, the optimal position for drag reduction presented a severe collision hazard, and drag savings were much more sensitive to lateral (wingtip) position than longitudinal (streamwise) position. By increasing longitudinal spacing, the collision hazard was greatly reduced and a 10-aircraft flock demonstrated a 9.7% reduction in total drag and 14.5% increase in endurance over a mock target.

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